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11 JUL 1978
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Prepared for

**U.S. DEPARTMENT OF ENERGY
Division of Solar Energy
Office of Energy Technology**

M78-15089

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April 1978

Prepared for
U. S. Department of Energy
Office of Energy Technology
Division of Solar Energy
Washington, D. C. 20545
Under Interagency Agreement E(49-26)-1028

WAKE CHARACTERISTICS OF A TOWER FOR THE DOE-NASA MOD-1 WIND TURBINE*

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SUMMARY

A 1/40th-scale model of a tower concept designed for the DOE-NASA MOD-1 wind power turbine was tested in a low-speed wind tunnel to determine the flow characteristics in the wake downwind of the tower. The tower model is a four-leg lattice type structure constructed with round members and gusset plates at the intersections of the members. Wind speed profiles were determined in a fixed plane downstream of the tower. Local values of wake minimum velocity ratio, average velocity ratio, and width were determined from these profiles, and these quantities were presented as a function of tower elevation for six wind approach angles from 0° to 45°. Over the elevations corresponding to the outer half of the rotor blade, the average value of the local ratios of minimum velocity to free-stream velocity varied from 0.68 to 0.73, while the average value of the local ratios of average velocity to free-stream velocity varied from 0.83 to 0.86 for the range of wind approach angles covered. The ratio of local wake width to projected local tower width varied from around 1.2 to 1.4 at the elevation of the blade tip to around 1.6 to 1.8 near the top of the tower.

The results from the MOD-1 tower model were compared to those of a MOD-0 tower model (also a four-leg lattice configuration, but without gusset plates) and an eight-leg model previously reported. All three towers were constructed with round members. The comparison was based on single mean values of ratio of average velocity defect to free-stream velocity and ratio of wake thickness to blade radius. At the plane of the rotor blade, both the mean velocity defect ratio and the mean width ratio were calculated to be slightly higher for the MOD-1 model than for the other two towers. Values for the mean velocity defect ratio were 0.20 for MOD-1 compared with 0.19 for MOD-0 and 0.16 for the eight-leg. Values for the mean width ratio were 0.37 for MOD-1 compared with 0.35 for MOD-0 and 0.33 for the eight-leg. For the two lattice-type models, the small increase in mean velocity defect ratio for MOD-1 compared to MOD-0 was probably due to the presence of gusset plates and relatively larger diameter cross members, while the increase in mean width ratio was attributed to a relatively larger tower width. The general geometric configuration of the MOD-1 tower (four-leg lattice construction) does not appear to be as favorable as the eight-leg tower concept for producing higher wake flow properties.

*This report was prepared with the assistance of Seymour Lieblein of Technical Report Services, Rocky River, Ohio 44116.

INTRODUCTION

A major element in the Department of Energy (DOE) Wind Energy Program is the development of large horizontal-axis, propeller type wind turbines (ref. 1). This effort involves the design, construction, and testing of three classes of experimental wind turbines with nominal rotor diameters of 125, 200, and 300 feet. These units are identified respectively as the MOD-0, MOD-1, and MOD-2 projects, all under the management of the NASA-Lewis Research Center (ref. 2).

The first of the experimental wind turbines, the DOE-NASA 100-kilowatt unit (the MOD-0) has been constructed and is currently being operated as a test bed (refs. 3 and 4). A 200-foot-diameter, 1800-kilowatt MOD-1 wind turbine is currently under final design. The overall objective of the MOD-1 wind energy project is to determine the operating and economic characteristics of a utility-operated megawatt-scale wind turbine, and to involve industry and potential users in the design, installation, and interface aspects of large wind systems.

To date, the wind turbines have been designed with the rotor operating on the downwind side of the supporting tower. Early operating experience with the 100-kilowatt unit (ref. 4) indicated that the defect in wind speed in the wake of the tower can excite substantial dynamic stresses in the rotor blades. Consequently, considerable effort is being exerted to determine the cause of and to reduce the adverse effects of tower wakes on blade stresses. The principal element of this effort is an experimental evaluation of the wake characteristics of tower models in a low-speed wind tunnel. Theoretical analysis of blade dynamic loading is also being conducted (ref. 5).

Results of wind-tunnel evaluations of the downwind wakes for the MOD-0 tower and for an eight-leg tower concept applicable to the MOD-0 class of turbines are presented in references 6 and 7. In these investigations, data are presented for the variation with tower elevation of such wake flow properties as the local minimum velocity, average velocity, and width over a range of wind approach angles. Wake velocities are nondimensionalized by the upwind free-stream value, while wake width is made nondimensional by both the tower width and the rotor blade radius.

Comparison of results of these early wind-tunnel investigations indicated that the major improvement in tower wake flow resulted from the elimination of the personnel stairway, the equipment elevator on one face of the tower, and from the use of tubular members. Furthermore, an all-tubular eight-leg tower concept produced a modest improvement in wake properties compared to the corresponding all-tubular, more conventional lattice tower design (MOD-0). Based on the results

of these tests, it should be possible to construct wind turbine towers with a ratio of average wake velocity defect to free-stream velocity of the order of 0.17 and a ratio of average wake width to blade radius of the order of 0.33.

During the preliminary design of the 1800-kilowatt MOD-1 wind turbine design, several tower configurations were considered. At that time, the concept of principal interest was a four-leg lattice-type design with round structural members with gusset plates at the major structural intersections. A drawing of the preliminary MOD-1 wind turbine design (with gusset plates deleted) is shown in figure 1. This tower design was generally similar to the tower configuration for the earlier MOD-0 wind turbine.

A 1/40th-scale model of the MOD-1 preliminary tower design was constructed for testing in a low-speed wind tunnel, as was done for the previous tower models described in references 6 and 7. The objective of these tests was to determine the wake flow characteristics of the MOD-1 tower design at various elevations behind the upper sections of the tower model (region of blade sweep) over a range of wind approach angles. It was also desired to compare the wake characteristics of the MOD-1 design with the MOD-0 configuration, and to determine any differences between them.

This report contains a description of the tower model, an outline of the test installation and procedure, the test results, and a comparison of these results with those of the all-tubular four-leg MOD-0 tower model and the all-tubular eight-leg tower concept of reference 7. Wake characteristics, presented in dimensionless form, include plots of the wind speed profiles and plots and tables of the vertical distribution of local minimum velocity, average velocity, and width. Mean values of these properties are then used as the basis for comparison with the other tower models.

APPARATUS AND TEST PROCEDURE

A scale model installed in a low-speed wind tunnel was selected as the test vehicle for determining the wake characteristics of the MOD-1 tower concept because of the simplicity and low cost with which the test could be conducted. Wind tunnel tests with scale models is a standard method for determining flow characteristics in the wake of various objects and is used to identify the principal factors affecting wake form and flow variations. The results of wind tunnel model tests are applicable to larger size configurations, provided the model is properly scaled geometrically and dynamically and the wake characteristics are similar.

It is recognized that a wind tunnel test cannot simulate the atmospheric wind flow patterns around a full-size tower. In addition to having a wind speed gradient close to the ground, natural wind flow generally has a different turbulence intensity and scale than tunnel air flow. (The free-stream turbulence level in the wind tunnel used for these tests is considerably greater than in other low-speed tunnels.) Also, the boundary conditions in the model case (no nacelle on top and no infinite ground plane at the base) can produce pressure fields and three-dimensional wake effects in the end regions of the tower that are different than in the full-scale situation. Nevertheless, the wind tunnel tests are very useful for making relative comparisons of different tower concepts and design changes, and for acquiring detailed wind speed profiles in the wake that are reasonably accurate representations of the profiles in the wake of the full-scale tower.

Model

A photograph of the 1/40th-scale model of the MOD-1 tower design is shown in figure 2. The tower is square in cross section at all elevations. At the top, the dimensions of the square is 4.0 by 4.0 inches. At the base, the dimensions are 12.75 by 12.75 inches. The vertical stations of the tower correspond to the elevations of the horizontal members above the tower base. Overall tower height is 43.6 inches. Table I lists the elevations of the horizontal sections and the outer dimensions of the square cross section of the tower.

All members of the tower model are circular in cross section. The diameter of the vertical legs is 5/16 inch, and the diameter of the horizontal and cross members is 7/32 inch. The gusset plates on the vertical legs are around 3/4 by $1\frac{3}{8}$ inches in cross-sectional area, while the gusset plates at the intersection of the cross members are around 11/16 by $1\frac{3}{8}$ inches in area.

The problem of wake formation downwind of such a tower in actual operation is illustrated in figure 3. In figure 3(a) is sketched a planview of the tower and a qualitative approximation of the outer limits of the region of wake flows generated by the members of the tower structure for the example cases of wind approaching at 0° and 45° . Also indicated is the interception of the wake by the plane of rotation of the rotor which is usually oriented to follow the wind direction. The vertical view of figure 3(b) shows the area of the wake region, $A_\delta = \delta_{av} R_b$, compared to the area swept by the rotating blades, $A_b = \pi R_b^2$. It can be seen that a significant portion of the blade travel is immersed in a reduced velocity field; that is, $A_\delta/A_b \sim \delta_{av}/R_b$. This suggests that the ratio δ/R_b is one of the important parameters to be determined.

The detailed form of the wake downwind of the tower depends on the individual wakes that are formed behind each structural member of the tower, how they progress downstream of each member, and how they interact with each other in the plane of the rotor (or measuring probe). Thus, the specific orientation of the tower members as projected on a downwind plane perpendicular to the wind direction can provide some insight into the wake-producing potential of a particular structural configuration. Such projections are obtained from shadow photographs of the tower structure over a range of wind approach angles. Shadow photographs of the MOD-1 tower model are shown for wind approach angles θ of 0° , 5° , 10° , 20° , 30° , and 45° in figures 4(a) through (f), respectively.

Installation

The MOD-1 tower model was installed in the test section of a 6- by 9-foot low-speed wind tunnel, as was done in the previous investigations (refs. 6 and 7). A photograph of the wind tunnel installation is shown in figure 2. During the tests, the base of the tower model was elevated off the floor of the tunnel in order to clear the ancillary equipment. The model could be rotated up to 90° with respect to the tunnel axis (approaching wind).

The wind speed profiles in the wake of the model were determined from measurements from a Pitot tube that was mounted on a remotely-controlled traveling carriage (fig. 2). Vertical and horizontal probe movement was provided. The total pressure sensed by the Pitot tube was referenced to a static pressure measured by a tap on the tunnel wall. Earlier surveys had indicated a sufficiently uniform static pressure at the measuring plane to allow wake velocity determination based on a fixed static pressure value. The velocity head (total minus static pressure) was sensed by a differential pressure gage of the variable-inductance type. A separate probe was used to determine the free-stream wind speed V_0 .

All wake profile measurements were made in a plane $13\frac{1}{8}$ inches downstream of the vertical centerline of the tower model. This distance is 1.5 times the width of the tower at station 2 for a wind approach angle $\theta = 0^\circ$. This distance ratio was selected to be consistent with the tests of the earlier models of reference 6, where the measuring plane was chosen to be 1.5 times the width of the tower at a reference level close to the lowest elevation that the tips of the blades achieve during operation (station 2 for the MOD-1 tower).

Pertinent properties and dimensions for the model installation and measurement are given in figure 5. Geometric parameters in the vertical plane are shown to scale in figure 5(a), and the important

wake flow parameters are identified in figure 5(b). These are the local values of: minimum velocity, $V_{\min}$; average velocity V_{av} ; average velocity defect $\Delta V_{av} = V_0 - V_{av}$; and width δ . Values of the parameters X_ℓ , X_b , and W , which vary with tower elevation, are tabulated in table I. Symbols are defined in appendix A. Values of the tower projected outer width W were determined from measurements of the tower model. The variation of projected outer width from station 2 ($H = 14.13$ in.) to station 6 ($H = 40.5$ in.) was linear according to the relation

$$W = (11.29 - 0.18 H)(\sin \theta + \cos \theta) \quad (1)$$

Inasmuch as the measuring station is a short distance downwind of the rotor plane of rotation, the wake properties determined in the tests are not exactly the same as those in the plane of the rotor. However, because of the short distance involved, the wake flow properties at the measuring station are not expected to vary substantially from those in the plane of rotation. Fluid speed deficits in the wakes behind blunt objects are persistent and require long distances to be dissipated.

Test Procedure

Horizontal wind speed profiles behind the tower were determined at varying vertical intervals over the upper four sections of the tower (stations 2 to 6, fig. 5(a)). This was done by positioning the probe at the desired elevation in the free stream. Then the probe was made to slowly travel horizontally from the free stream on one side to the free stream on the other. This procedure resulted in a continuous recording of the local flow profile at each elevation. A complete set of profiles was measured for each wind approach angle θ of 0° , 5° , 10° , 20° , 30° , and 45° .

All measurements were made at a nominal wind speed of 100 mph and at ambient temperature and pressure (close to atmospheric). For these tunnel air flow conditions, the Reynolds number for the tower model based on the diameter of the legs of 0.313 inch is 2.29×10^4 . The MOD-1 Wind Turbine Generator usually operates in winds from 10 to 40 mph and in air temperature from about 0° to 100° F. The range of Reynolds number for these conditions is from 5.4×10^4 to about 3.5×10^5 . For flow over a smooth slender cylinder, the drag coefficient is essentially constant for Reynolds numbers from about 10^3 to 4×10^5 . From momentum and similarity considerations, the constancy of the drag coefficient implies that the dimensionless velocity profiles downstream of the cylinder are identical for values of Reynolds numbers within this range. Since the tower model is made of all tubular members, there should be no difference, due to Reynolds number effects, in the dimensionless wind speed profiles in the wake of a full-scale tower compared to those of the model.

The survey probe and wall tap signals were converted to local velocity ratio V/V_0 by means of an analog module and plotted as a continuous on-line trace to show the wake profile. Damping was provided in the output circuit to reduce local turbulent fluctuations in the wake. However, even with the damping, the printed velocity ratio trace contained high-frequency fluctuations as large as several percent. A precise determination of the mean value of the velocity variation was consequently difficult to obtain. For simplicity, each profile trace was smoothed to a single faired variation according to best judgment. The faired profile was then digitized and processed to establish the minimum velocity ratio $V_{\min}/V_0$ and the integrated average velocity ratio V_{av}/V_0 . Velocity ratio values for the faired profiles were calculated and presented herein to three significant figures, with the values of $V_{\min}/V_0$ rounded off to the nearest 0.005. However, it is recognized that such presentation implies a higher degree of precision than exists in reality for the wake mean velocity.

For the determination of wake width, the edges of the wake were selected from the faired curves to be the points where the local velocity ratio V/V_0 increased to a value of about 0.995. Clearly, from the manner in which the profiles gradually approach the free-stream value, a precise measure of the wake width was difficult to determine.

WAKE FLOW CHARACTERISTICS

The presentation of wake characteristic data obtained from the wind tunnel surveys will include illustrations of the wake velocity profiles and the variations with tower elevation and wind direction of the properties of local wake minimum velocity ratio, average velocity ratio, and width. A complete tabulation of these data parameters is given in table II.

Velocity Profiles

Representative measured wind speed profiles from the continuous trace output are shown in figures 6 and 7. Figure 6 shows the variation of wake velocity profile with wind approach angle downstream of the tower at an elevation $H = 20.95$ inches. This elevation is very close to the location of the horizontal members of station 3 (figs. 4 and 5(a)). At this location, the downstream velocity profile is expected to be determined by the superposition of the wake from the horizontal member and from the end gusset plates (intersection of the vertical, cross, and horizontal members). A relatively deep wake would therefore be expected. This is found to be the case in figure 6, with minimum velocity ratios reaching to between 0.6

and 0.7. At $\theta = 0^\circ$ (fig. 6(a)), two essentially symmetrical troughs are seen (relates to fig. 4(a)), while at $\theta = 45^\circ$ (fig. 6(f)), a three-trough symmetrical profile is obtained (relates to fig. 4(f)). Intermediate profiles are seen for the intermediate angles.

Figure 7 shows wake profiles at an elevation slightly below the intersection of the cross members between stations 3 and 4. Thus, according to the shadow photographs of figures 4(a) and (f), a four-trough symmetrical profile should be expected at $\theta = 0^\circ$, and a five-trough profile at $\theta = 45^\circ$. This is indeed the case, as shown in figures 7(a) and (f). The center trough at $\theta = 45^\circ$ (fig. 7(f) as well as 6(f)) is deeper than the end ones because, at that orientation, there are two legs in line at the center compared to only one at each end. Furthermore, since no horizontal members or gusset plates are involved at this elevation, the wake velocity defect should be less than that for the earlier elevation. Minimum velocity ratios in figure 7 range between 0.7 and 0.8, compared to between 0.6 and 0.7 in figure 6.

The illustrative wake profiles presented in figures 6 and 7 demonstrate the complex nature of the velocity distributions downwind of the tower. In general, each distribution is determined by the number of members and their relation and proximity to each other. A good qualitative indication of this can be given by the shadow photographs of the tower over a range of wind approach angles (e.g., fig. 4). For members with circular cross-sections, the velocity distribution immediately downwind of a round member may be close to that of a circular cylinder. However, the velocity reduction in the wake of a member is generally reduced further when there are other members close to it, intersecting with it, or upwind from it. Conversely, when the separation between members is increased, the velocity defects are smaller and flow through the tower is increased. Thus, the shape of the wake at some distance downstream of a tower (i.e., at the measuring station, or in the plane of the rotor blade) at any elevation is a superposition and coalescence of the wakes of the individual members.

Additional wake profile traces over a wide range of tower elevations and wind approach angles are given in appendix B.

Minimum and Average Velocities

Results for the vertical variation of minimum velocity ratio $V_{\min}/V_0$ and average velocity ratio V_{av}/V_0 for each test profile are plotted in figure 8 for wind approach angles from 0° to 45° . Data are presented for the tower sections from stations 2 to 6. The elevations of the tower stations are identified on the figure together with the elevations corresponding to the rotor blade tip and to the point at half of the blade radius (defines the location of the outer 50 percent of the blade).

The plots of figure 8 show rather large variations of $V_{\min}/V_0$ with elevation at all angles. The lowest values of this ratio appear to occur at the elevations of the horizontal members, with the highest values appearing approximately midway between the horizontal members. This general trend with location was indicated by the illustrative profile traces at the two elevations shown in figures 6 and 7. The large variations of $V_{\min}/V_0$ with elevation in figure 8 are not surprising in view of the complex interactions of the wakes from the individual members, as was discussed in the previous section. The resultant value of minimum velocity ratio is a manifestation of the different ways in which the individual wakes from the tower structural members superimpose and coalesce at the location of the measuring plane.

The variation of V_{av}/V_0 with elevation in figure 8 is smaller than for the minimum velocity ratio. As in the case of the minimum velocity ratio, the minimum values of V_{av}/V_0 occur at the horizontal members, while the maximum values occur in between the stations. This trend is especially apparent for the lower sections. On the average there appears to be a slight tendency for the average velocity to decrease with increasing elevation.

The effect of the wake on rotor blade stresses is largely determined by the flow conditions over the outer half of the blade (e.g., ref. 5). Accordingly, arithmetic average values of $V_{\min}/V_0$ and V_{av}/V_0 were determined for the tower elevations from R_b to $1/2 R_b$ for each wind approach angle. These values, indicated by the dashed lines, are listed in figure 8. The average velocity ratio shows a relatively small variation with θ . This result implies that wind approach angle is not an important variable in determining the average wake velocities over the outer half of the blade for the MOD-1 tower. Such an observation can also be made on the basis of the composite plots of all values of $V_{\min}/V_0$ and V_{av}/V_0 shown in figure 9.

Width

It was expected that the principal determinant of the width of the wake from the tower would be the projected width of the tower structure onto a plane normal to the wind approach angle. Accordingly, the measured wake width δ was expressed as a ratio of the projected tower width W . Plots of the ratio δ/W are given in figure 10 for the six wind approach angles. Also shown on each figure are the elevations of the tower stations and the outer 50 percent of the blade.

The principal characteristic of the δ/W data shown in figure 10 is the increase in value with increasing elevation for all angles. At the low values of θ , there seems to be concurrence of the points of minimum δ/W and the elevation of the horizontal members (tower

stations). There is also a slight tendency of the wake width values to decrease with increasing wind approach angle. However, for values of θ from 10° to 45° , the values of δ/W are approximately the same. This basically verifies the premise that the tower projected width is the principal determinant of the width of the wake. In the angle range from 10° to 30° , the ratio δ/W varies from around 1.2 at station 2 to around 1.6 at station 6. The ratio then increases as θ is decreased, until values from around 1.4 to 1.9 are attained at $\theta = 0^\circ$.

As indicated previously, the significant wake factor affecting rotor blade dynamics is the ratio of wake width to blade radius, δ/R_b . Figure 11 presents the variation of this parameter with elevation for the six wind approach angles. Also shown on the figure is the variation of the ratio of tower width to blade radius W/R_b . According to the results of the preceeding discussion of δ/W , the variation of δ/R_b is expected to be closely related to the variation of W/R_b at each orientation.

Figure 11 does indeed show that the values of δ/R_b follow the variations of W/R_b : the wake width ratio decreases with elevation; and, at a given elevation, it increases with wind approach angle. For the range of elevations covering the outer half of the blade (R_b to $1/2 R_b$), δ/R_b decreases with elevation from around 0.4 to 0.31 at $\theta = 0^\circ$ (fig. 11(a)). These values then increase with angle to give around 0.48 to 0.37 at $\theta = 45^\circ$ (fig. 11(f)). An overall average value of δ/R_b for the outer half of the blade for wind approach angles from 0° to 45° is around 0.40.

COMPARISON WITH OTHER TOWER MODELS

In evaluating the wake performance of the MOD-1 tower model, it is desirable to compare its wake characteristics with those of other available tubular-model towers. To date, two other tower models have been tested in the same low-speed wind tunnel: the all-tubular model of the four-leg MOD-0 tower discussed in references 6 and 7; and the eight-leg MOD-0 type model investigated in reference 7.

Models

A photograph of the three tower models is presented in figure 12. A comparison sketch of the three models drawn to their actual dimensions is given in figure 13 for a wind approach angle $\theta = 0^\circ$, and in figure 14 for $\theta = 45^\circ$. Also shown on the figure are the elevations corresponding to the outer half of the rotor blade (R_b to $1/2 R_b$) for each tower. A listing of the geometric properties of interest for the models is given in table III. It should be noted that since the

models were constructed from tubular stock of standard sizes, it is not possible to obtain a precise scaling of the diameters of the tubular members. The outer diameters of the members of the MOD-1 tower model are indicated on page 4. Member diameters for the MOD-0 and eight-leg models are given in reference 7.

A summary of wake flow characteristics is listed in table II herein for the MOD-1 model, and in tables II and V of reference 7 for the eight-leg and MOD-0 towers, respectively. These tabulations list the local values of wake minimum velocity ratio $V_{\min}/V_0$, average ratio V_{av}/V_0 , and width δ for each tower.

During normal operation, each rotor blade is totally immersed in the wake for a short period of time which depends on the wake width and the rotor rpm. It is during this time period that the wake average velocity defect imposes an impulse force on the blade. Thus, the important consideration for each tower is the width of the wake with respect to the radius of the blade. Thus, the wake width data for each tower was expressed as the ratio δ/R_b .

The basis for comparison of the wake characteristics of the three tower models was the arithmetically averaged values of local $V_{\min}/V_0$, V_{av}/V_0 , $\Delta V_{av}/V_0$, and δ/R_b over the outer half of the rotor blade (R_b to $1/2 R_b$) for each wind approach angle. Wake flow conditions over the outer half of the blade are used in analysis of blade dynamics (e.g., ref. 5). A summary of such averaged values is given in table IV for the three towers. These values represent the average wake characteristics at the respective measuring station locations of the models.

Velocity Ratios

Measuring station location. - At the measuring station of each model, according to table IV, the averaged minimum velocity ratios $(V_{\min}/V_0)_{av}$ of the MOD-1 tower are substantially greater than those of the MOD-0 tower, but less than those of the eight-leg tower. A corresponding comparison of the averaged values of average velocity $(V_{av}/V_0)_{av}$ shows the MOD-1 tower to be close to the MOD-0 tower, but not as favorable as the eight-leg tower. This comparison is shown graphically by the plot of averaged average velocity defect ratio $(\Delta V_{av}/V_0)_{av}$ against wind approach angle θ in figure 15(a). The MOD-1 tower variation is very close to the MOD-0 results in both form and magnitude. The averaged values of $\Delta V_{av}/V_0$ for the eight-leg model, however, is significantly lower than for both of the four-leg configurations.

The variation of $(\Delta V_{av}/V_0)_{av}$ with θ for the towers in figure 15(a) is probably related to the variation of tower shadow solidity with wind approach angle. For example, as θ increases from 0° to 10° , both the average velocity defect ratio and the shadow solidity increase (i.e., fig. 4 for MOD-1). The very close similarity of the trends for the MOD-0 and MOD-1 towers is undoubtedly due to their close geometric similarity. Overall, figure 15(a) suggests that the basic configuration of a tower has only a small effect on the directional dependence of the average velocity defect.

Blade location. - As indicated in table III, the sizes and measuring station locations of all three tower models are different. Thus, comparisons of wake characteristics at their respective measuring station locations may not be a true measure of the relative performance of the towers. Inasmuch as the key issue is the influence of the tower wake on blade dynamic behavior, the data were extrapolated to allow a comparison on the basis of their respective blade locations. The plane of the rotor blade in all three cases is not perpendicular to the horizontal axis of the rotor (e.g., fig. 1). Therefore, the representative axial location for the plane of the blade was taken as the axial distance from the vertical axis of the tower to the 3/4-radius point of the blade (center of the outer half of the blade). These locations, which are closer to the tower than the measuring stations (fig. 7(a)), are listed in table III.

In correcting the data from measuring station to blade location for each tower, it was necessary to employ a simplified model of the wake dissipation. The basic assumption is that the overall development of the wake from the tower is largely determined by the wake development of slender isolated cylinders (as represented by the lower legs), and that changes in tower wake characteristics can be adequately described by changes in classical cylinder wake behavior with downstream distance.

As indicated in table III, the measuring station locations based on the diameters of the tower legs $(X/d_t)_m$ vary from 30 to 62.25 for the towers. Since these values are relatively high, it is assumed that the classical variation for fully-developed wake flow far downstream of a slender cylinder (e.g., ref. 8) is applicable to the tower wake; that is,

$$\left(1 - \frac{V_{min}}{V_0}\right) \sim \left(\frac{X}{d_t}\right)^{-1/2} \quad (2)$$

A further useful assumption is that the minimum and average velocity ratios of a wake are related by the expression

$$b = \frac{1 - \left(\frac{V_{av}}{V_0} \right)}{1 - \left(\frac{V_{min}}{V_0} \right)} \quad (3)$$

which is essentially constant for the range of X values covered. This assumption is correct for fully developed wake flow with similar profiles (ref. 8). The relation for the general variation of average velocity defect ratio with distance upstream of the measuring station (location m) is then given by

$$\frac{\left(\frac{\Delta V_{av}}{V_0} \right)}{\left(\frac{\Delta V_{av}}{V_0} \right)_m} = \sqrt{\frac{\left(\frac{X}{d_t} \right)_m}{\left(\frac{X}{d_t} \right)}} \quad (4)$$

For simplicity in the application of equation (4), a single mean value of average velocity defect ratio $(\overline{\Delta V_{av}/V_0})_{av}$ was determined at the measuring station for each tower. This mean value was obtained as the integrated value of $(\Delta V_{av}/V_0)_{av}$ over the angle range $0^\circ \leq \theta \leq 45^\circ$ (fig. 15(a)). It was then assumed that equation (4), developed for the local wake values, is also applicable to mean values as defined above. The variation in mean value $(\overline{\Delta V_{av}/V_0})_{av}$ from the measuring station $(X/d_t)_m$ to the blade plane $(X/d_t)_b$ was then calculated for each of the towers with the use of equation (4). Plotted results are shown in figure 15(b), and the end values are listed in table V.

From figure 15(b) and table V, it is seen that the wake mean average velocity defect ratio at the blade plane of the MOD-1 tower model is calculated to be slightly larger than that of the MOD-0 model, and significantly larger than that of the eight-leg model. Furthermore, the theoretical curve for the MOD-1 model is displaced above the curves of the MOD-0 and eight-leg models which tend to form a single approximately continuous variation. This near concurrence of the MOD-1 and eight-leg curves suggests, that in the case of the eight-leg tower, the relatively smaller-diameter legs, the absence of cross members, and the relatively few joints may tend to compensate for the increased number of legs.

For the MOD-1 model, the small increase in the level of $(\overline{\Delta V_{av}/V_0})_{av}$ over the MOD-0 curve may be the result of relative differences in the

geometry of the tower members. Two major contributory differences are noted for the MOD-1 tower: the presence of gusset plates at the intersections; and the relatively larger diameter cross members (table III). The presence of two significant geometric differences contributing to the relatively small increase in the $(\Delta V_{av}/V_0)_{av}$ curve for the MOD-1 model suggests that, in general, the presence of gusset plates by themselves has only a negligible influence on mean average velocity defect ratio. This same conclusion was reached from an unpublished analysis of the tower drag characteristics of the MOD-1 model and a similar all-tubular model without gusset plates.

The apparent small effect of gusset plates on wake mean velocity defect is believed the result of the large flow resistance produced by the underlying joints. Examination of wind speed profiles shows that the joint areas produce a much greater flow resistance than the individual members or when the members are in line. Thus, the physical addition of the gusset plates over the joints does not contribute much additional flow blockage. This also suggests that the average velocity defect in the tower wake can be reduced by reducing the number of joints as well as the size and the number of members that form the necessary joints.

If the preceding interpretation of the differences in wake velocity defect is correct, small adjustments in the tower geometry could allow the MOD-1 curve in figure 15(b) to coincide with the lower curve. Thus, a mean value of average velocity defect ratio of 0.17 could probably be achieved at the blade for a full-scale MOD-1 tower.

Width

Measuring station location. - The comparison of wake width ratio δ/R_b for the three towers was conducted in a manner similar to that of the average velocity defect just described. The variation of the average value of wake width-to-blade radius $(\delta/R_b)_{av}$ at the measuring station was first plotted against wind approach angle θ for the three tower models in figure 16(a). It is seen from the figure that the wake width of the MOD-1 tower is significantly larger in relation to the blade length than those of both the MOD-0 and eight-leg towers. The larger wake width ratios for the MOD-1 tower compared to the other two models are attributed to relatively larger values of tower width. Tower width W for MOD-1 is given by equation (1), while values for the eight-leg and MOD-0 models are given in reference 7.

The values of $(\delta/R_b)_{av}$ for the MOD-1 and MOD-0 models in figure 16(a) increase in a roughly similar fashion with increasing wind approach angle. Again, the increase in δ/R_b with wind approach

angle is due to the increase in tower projected width W as θ is increased. Projected width varies similarly with θ for these two towers (e.g., eq. (1) for MOD-1). However, for the eight-leg tower, the average W for the outer half of the blade remains more nearly constant between $\theta = 30^\circ$ and 45° (ref. 7). This accounts for the leveling of the width ratio in that range.

Blade location. - For the comparison at the plane of the blade, a mean value of average width ratio $(\delta/R_b)_{av}$ was first established for each model. Corresponding values at the blade plane were then calculated from consideration of a highly simplified model of the wake width. This model is based on the simplifying assumption that the width of the tower wake can be represented as the outer limits of the wakes generated by two identical circular cylinders with diameter equal to the tower leg diameter d_t and with centerline separation distance equal to $(W - d_t)$. The quantity W , representing the width of the tower, is the overall projected width of the tube pair. Thus, with the wake of the individual cylinder denoted by δ_t , the overall (tower) wake at any elevation is given by

$$\delta = (W - d_t) + \delta_t \quad (5)$$

or

$$\frac{\delta}{d_t} = \left(\frac{W}{d_t} - 1 \right) + \frac{\delta_t}{d_t} \quad (6)$$

For classical fully-developed wake flow,

$$\frac{\delta_t}{d_t} \sim \sqrt{\frac{X}{d_t}} \quad (7)$$

Thus, the wake width at an upstream location (X/d_t) is related to the value at the measuring plane $(X/d_t)_m$ by

$$\frac{\left(\frac{\delta}{d_t} \right) - \left(\frac{W}{d_t} - 1 \right)}{\left(\frac{\delta}{d_t} \right)_m - \left(\frac{W}{d_t} - 1 \right)} = \sqrt{\frac{\left(\frac{X}{d_t} \right)}{\left(\frac{X}{d_t} \right)_m}} \quad (8)$$

Calculated values of mean width ratio $(\delta/R_b)_{av}$ from the measuring plane to the blade plane for each tower as obtained from equa-

tion (8) are plotted in figure 16(b). Values at the limits of the plots are also listed in table V. It is seen in figure 16(b) and table V that the MOD-1 tower continues to show the largest value of mean width ratio up to the blade plane with a value of 0.37 compared to 0.35 for the MOD-0 model, and to 0.33 for the eight-leg model.

As indicated earlier, the larger values of wake width for the MOD-1 tower are attributed to relatively larger values of tower width. Values of ratio of mean tower width to blade radius $(\bar{W}/R_b)_{av}$ (mean $\bar{W}$ is determined the same way as mean δ) listed for the three models in table III show a decrease in value for MOD-1 to eight-leg with roughly the same percentage variation as the corresponding decrease in $(\delta/R_b)_{av}$. This relation for the plane of the rotor blade is shown more graphically in figure 17. A straight line from the origin correlates the calculated points for the three models very well. Thus, the mean wake width ratio of a tower can be reduced by decreasing the tower width. In particular, a mean wake width ratio of around 0.34 could readily be obtained for the MOD-1 model with a small percentage decrease in tower width.

SUMMARY OF RESULTS

Comparison of the wake characteristics of the all-tubular MOD-1 model (with gusset plates) with those of the all-tubular MOD-0 model at the blade plane showed only relatively small differences in wake mean velocity defect and width ratios. Analysis of the data indicated that the small differences in wake characteristics were probably related to small differences in structural configuration and dimensions. These physical differences among the models were due to inexact scaling of the individual members as well as to basic differences in geometric concept or configuration.

The slightly larger tower shadow of the MOD-1 model compared to the MOD-0 model was attributed to the presence of gusset plates and relatively larger diameter cross members. For the comparison between the MOD-1 and eight-leg models, the slightly superior wake performance of the eight-leg model was attributed to a basically more favorable geometric configuration. For the eight-leg model, the relatively smaller leg diameter, the absence of cross members, and the relatively fewer joints appear to more than compensate for the increased number of vertical members.

On the basis of the results and analysis contained herein, it should be possible to achieve a value of mean average velocity defect ratio of around 0.17 and a value of mean ratio of wake width to blade radius of around 0.34 at the blade plane for a full-scale, all-tubular lattice-type tower for the MOD-1 wind turbine.

APPENDIX A

SYMBOLS

Most of the symbols used herein are denoted in figure 7.

A	area, in ²
b	ratio of local defect in average velocity to defect in minimum velocity
d_t	diameter of leg of tower, in.
H	local tower elevation (height) above the base, in.
H_a	elevation of horizontal axis of rotor blades, in.
H_b	minimum height of rotor blade tip above the base of the tower, in.
R_b	radius of the tip of the rotor blade, in.
V	local wind speed in wake, mph
V_{av}	arithmetic average wind speed in wake at any local elevation, H , mph
V_{min}	minimum wind speed in wake at any local elevation, H , mph
V_0	approaching free-stream wind speed, mph
ΔV_{av}	defect in the average velocity, $V_0 - V_{av}$, mph
$(\overline{\Delta V_{av}})_{av}$	mean value of average velocity ratio over outer half of the blade (integrated over range of θ), mph
W	local projected width of tower in plane normal to approaching angle, in.
W_{ref}	projected width of the tower legs at the elevation of the blade tip for the 0° wind direction orientation, in.
$\overline{W}_{av}$	mean value of average projected tower width over outer half of the blade (integrated over range of θ), in.
X	local distance downstream from the vertical centerline of the tower, in.

- X_b local distance between the vertical centerline of the tower and the plane of the centerline of the blade, in.
- X local distance between the measuring station and the most downwind leg of the tower ($X_m - X_t$), in.
- X_m distance between the vertical centerline of the tower and the measuring plane, in.
- X_t local distance between the vertical centerline of the tower and the most downwind leg of the tower, in.
- δ local horizontal width of the wake downstream of the tower, in.
- δ_t width of wake from individual tower leg, in.
- $\overline{\delta}_{av}$ mean value of average wake width over outer half of the blade (integrated over range of θ), in.
- θ angle between the approaching wind direction and a normal to the front side of the square tower, deg

APPENDIX B

WAKE VELOCITY PROFILES

A continuous trace of the velocity ratio in the wake was obtained for each tower elevation and wind approach angle. In all, around 260 wake profile traces were obtained and reduced. Sample traces at two elevations were shown in figures 6 and 7. The turbulent nature of the local wake flow is clearly indicated in these traces.

In view of the large number of data points involved, only 21 out of the 44 recorded elevations were included for presentation in this section of the report. These elevations were selected to provide a reasonably complete description of the variation in wake profile with elevation for each wind approach angle. The selected elevations are: 14.3, 15.2, 16.2, 17.1, 18.3, 19.0, 19.9, 21.1, 23.2, 24.2, 25.05, 26.05, 27.05, 27.55, 30.8, 33.65, 34.4, 37.4, 38.8, 40.25, and 40.75. The wake traces are shown in figures 18(a) through (f). Each part of figure 18 contains the variation of V/V_0 against horizontal distance for the 21 elevations at a given value of wind approach angle θ .

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TABLE II. - SUMMARY OF WAKE CHARACTERISTICS FOR MOD-1 TOWER MODEL^a(a) Wind approach angle, $\theta = 0^\circ$ (b) Wind approach angle, $\theta = 5^\circ$

Elevation, H, in.	Minimum velocity, $V_{\min}/V_0$	Average velocity, V_{av}/V_0	Width, δ , in.	Elevation, H, in.	Minimum velocity, $V_{\min}/V_0$	Average velocity, V_{av}/V_0	Width, δ , in.
13.90	0.655	0.786	12.00	13.90	0.640	0.784	11.73
14.30	.635	.796	12.00	14.30	.630	.799	11.60
14.80	.640	.804	12.13	14.80	.630	.798	11.73
15.20	.635	.827	12.40	15.20	.625	.818	12.13
15.40	.645	.837	12.40	15.40	.650	.828	12.13
15.60	.670	.841	12.13	15.60	.680	.840	12.13
15.75	.690	.844	12.27	15.75	.705	.845	12.27
16.20	.735	.835	12.00	16.20	.725	.843	12.27
16.70	.765	.836	11.73	16.70	.735	.842	11.87
17.10	.770	.852	11.73	17.10	.735	.855	11.73
17.50	.770	.870	11.73	17.50	.735	.869	11.73
17.90	.750	.880	11.87	17.90	.730	.876	11.87
18.30	.745	.868	11.87	18.30	.725	.859	11.87
18.60	.740	.858	11.73	18.60	.725	.850	11.73
19.00	.735	.845	11.87	19.00	.730	.843	11.87
19.50	.710	.828	11.60	19.50	.715	.828	11.47
19.90	.685	.812	11.33	19.90	.685	.819	11.33
20.30	.700	.806	10.93	20.30	.700	.805	10.80
20.70	.705	.808	10.53	20.70	.690	.808	10.53
20.95	.690	.808	10.53	20.95	.680	.797	9.87
21.10	.685	.811	10.80	21.10	.680	.804	10.40
21.50	.675	.811	10.80	21.50	.665	.809	10.80
22.00	.680	.826	10.93	22.00	.665	.823	10.93
22.70	.700	.832	11.20	22.70	.685	.810	11.07
23.20	.700	.825	11.20	23.20	.700	.839	11.20
23.70	.730	.849	11.20	23.70	.735	.846	11.20
24.20	.780	.846	10.80	24.20	.740	.846	11.07
24.55	.775	.854	10.80	24.55	.745	.858	10.80
25.05	.780	.871	10.67	25.05	.745	.868	10.80
25.55	.765	.877	10.67	25.55	.735	.864	10.80
26.05	.760	.859	10.67	26.05	.720	.840	10.80
26.55	.750	.832	10.53	26.55	.725	.829	10.67
27.05	.720	.828	10.40	27.05	.690	.821	10.40
27.30	.715	.824	10.13	27.30	.685	.815	10.00
27.55	.720	.824	9.87	27.55	.695	.813	9.73
30.80	.750	.832	9.33	30.80	.735	.831	9.60
33.65	.735	.814	8.27	33.65	.675	.797	8.27
33.90	.725	.833	8.67	33.90	.665	.817	8.53
34.15	.715	.834	8.27	34.15	.660	.820	8.40
34.40	.710	.835	8.67	34.40	.665	.816	8.53
37.40	.750	.830	7.87	37.40	.735	.819	8.00
38.80	.735	.809	8.00	38.80	.740	.822	8.13
40.25	.710	.831	7.20	40.25	.665	.790	8.00
40.75	.745	.846	7.73	40.75	.640	.778	7.47

^aThe values of V_{av}/V_0 and $V_{\min}/V_0$ listed are probably one significant figure more than is justified by the accuracy.

TABLE II, - Continued.

(c) Wind approach angle, $\theta = 10^\circ$ (d) Wind approach angle, $\theta = 20^\circ$

Elevation, H, in.	Minimum velocity, $V_{\min}/V_0$	Average velocity, V_{av}/V_0	Width, δ , in.	Elevation, H, in.	Minimum velocity, $V_{\min}/V_0$	Average velocity, V_{av}/V_0	Width, δ , in.
13.90	0.630	0.787	12.67	13.90	0.655	0.808	14.53
14.30	.615	.794	12.80	14.30	.635	.808	14.27
14.80	.625	.794	12.67	14.80	.640	.808	14.13
15.20	.660	.816	12.93	15.20	.700	.826	14.27
15.40	.680	.828	12.93	15.40	.720	.840	14.40
15.60	.700	.840	12.80	15.60	.730	.854	14.13
15.75	.715	.849	12.80	15.75	.735	.864	14.00
16.20	.745	.856	12.93	16.20	.755	.871	13.33
16.70	.745	.845	12.27	16.70	.760	.863	12.93
17.10	.735	.851	12.13	17.10	.765	.851	13.07
17.50	.735	.852	12.00	17.50	.760	.849	13.07
17.90	.745	.850	12.13	17.90	.755	.851	13.07
18.30	.750	.833	12.13	18.30	.760	.849	12.93
18.60	.745	.831	12.00	18.60	.755	.845	12.80
19.00	.745	.836	12.13	19.00	.745	.845	12.67
19.50	.700	.825	11.73	19.50	.690	.843	12.40
19.90	.665	.817	11.47	19.90	.660	.840	12.67
20.30	.655	.799	11.20	20.30	.665	.833	12.93
20.70	.650	.812	11.33	20.70	.665	.828	12.53
20.95	.645	.807	11.07	20.95	.680	.831	12.53
21.10	.650	.804	11.20	21.10	.695	.830	12.53
21.50	.670	.810	11.60	21.50	.695	.833	12.93
22.00	.680	.823	11.60	22.00	.705	.835	12.80
22.70	.680	.816	11.87	22.70	.705	.833	12.80
23.20	.725	.841	11.87	23.20	.755	.844	12.67
23.70	.760	.853	11.73	23.70	.770	.853	12.13
24.20	.760	.870	12.00	24.20	.775	.855	11.73
24.55	.740	.862	11.07	24.55	.775	.848	11.73
25.05	.725	.852	11.07	25.05	.775	.845	11.73
25.55	.730	.835	11.07	25.55	.770	.845	11.73
26.05	.755	.821	10.93	26.05	.760	.840	11.47
26.55	.725	.826	10.53	26.55	.745	.838	11.47
27.05	.680	.809	10.26	27.05	.680	.828	11.07
27.30	.680	.807	10.13	27.30	.680	.821	10.93
27.55	.680	.808	10.00	27.55	.685	.815	10.80
30.80	.710	.824	9.73	30.80	.745	.822	10.27
33.65	.650	.796	9.07	33.65	.665	.792	9.73
33.90	.640	.800	9.07	33.90	.660	.805	9.87
34.15	.640	.811	9.07	34.15	.655	.808	9.73
34.40	.640	.799	8.93	34.40	.650	.801	9.60
37.40	.680	.792	8.13	37.40	.700	.779	8.80
38.80	.685	.789	8.13	38.80	.700	.780	8.93
40.25	.620	.777	8.00	40.25	.620	.770	8.40
40.75	.590	.757	7.60	40.75	.590	.755	8.46

TABLE II. - Concluded.

(e) Wind approach angle, $\theta = 30^\circ$ (f) Wind approach angle, $\theta = 45^\circ$

Elevation, H, in.	Minimum velocity, $V_{\min}/V_0$	Average velocity, V_{av}/V_0	Width, δ , in.	Elevation, H, in.	Minimum velocity, $V_{\min}/V_0$	Average velocity, V_{av}/V_0	Width, δ , in.
13.90	0.650	0.825	14.40	13.90	0.610	0.824	15.33
14.30	.625	.814	14.53	14.30	.600	.806	15.60
14.80	.635	.823	14.40	14.80	.595	.827	15.47
15.20	.685	.841	14.40	15.20	.625	.855	14.60
15.40	.715	.852	14.53	15.40	.650	.874	15.07
15.60	.740	.858	14.40	15.60	.685	.884	14.53
15.75	.745	.864	14.27	15.75	.710	.887	14.13
16.20	.760	.868	13.73	16.20	.735	.893	13.60
16.70	.740	.870	13.73	16.70	.730	.890	13.87
17.10	.735	.867	13.87	17.10	.720	.873	14.27
17.50	.755	.866	13.87	17.50	.710	.851	14.40
17.90	.765	.861	13.87	17.90	.715	.835	14.40
18.30	.740	.848	13.73	18.30	.730	.835	14.27
18.60	.750	.837	13.87	18.60	.725	.847	14.13
19.00	.770	.844	13.60	19.00	.700	.861	13.87
19.50	.685	.843	12.93	19.50	.650	.864	13.33
19.90	.660	.848	13.07	19.90	.635	.859	13.20
20.30	.665	.845	13.07	20.30	.635	.851	13.47
20.70	.680	.833	12.93	20.70	.650	.837	14.40
20.95	.675	.831	13.07	20.95	.650	.829	14.27
21.10	.680	.833	12.93	21.10	.650	.832	14.27
21.50	.680	.847	13.07	21.50	.655	.865	14.27
22.00	.690	.852	13.07	22.00	.665	.872	13.73
22.70	.685	.847	13.33	22.70	.635	.857	14.13
23.20	.735	.856	13.07	23.20	.670	.864	13.33
23.70	.780	.856	12.53	23.70	.700	.868	12.40
24.20	.770	.865	12.40	24.20	.750	.882	12.40
24.55	.755	.874	13.07	24.55	.745	.878	12.53
25.05	.750	.861	12.40	25.05	.725	.858	12.80
25.55	.755	.846	12.40	25.55	.720	.837	12.67
26.05	.755	.835	12.27	26.05	.710	.838	12.53
26.55	.715	.826	11.73	26.55	.660	.841	12.00
27.05	.670	.831	11.47	27.05	.650	.842	11.33
27.30	.670	.836	11.60	27.30	.655	.846	11.60
27.55	.680	.837	11.47	27.55	.670	.847	12.00
30.80	.760	.836	10.80	30.80	.720	.850	11.07
33.65	.645	.803	9.73	33.65	.665	.828	10.53
33.90	.655	.808	9.73	33.90	.680	.825	10.93
34.15	.655	.807	9.73	34.15	.675	.817	11.07
34.40	.655	.811	9.73	34.40	.680	.816	11.20
37.40	.700	.804	9.33	27.40	.680	.817	9.47
38.80	.685	.800	9.33	38.80	.680	.816	9.47
40.25	.595	.757	8.93	40.25	.580	.766	9.20
40.75	.590	.776	8.67	40.75	.635	.793	8.67

TABLE III. - GEOMETRIC PROPERTIES OF TOWER MODELS

Property	Tower model		
	MOD-1	MOD-0	Eight-leg
Scale	1/40	1/48	1/25
Height, H_a , in.	43.6	23.25	44.40
Blade radius, R_b , in.	31.2	15.625	30.0
Diameter of leg, d_t , in.	0.3125	0.1875	0.250
Diameter of cross member, in.	0.219	0.0938	-----
Downstream distance of measuring station, X_m , in.	13.13	5.625	15.563
Reference tower width, W_{ref} , in.	8.75	3.75	7.45
Mean tower width for outer 50 percent of blade, $\bar{W}_{av}$, in.	8.92	4.08	7.36
Downstream distance of blade at $3/4 R_b$, X_b , in.	8.0	3.90	8.03
X_m/d_t	42.0	30.0	62.25
X_b/d_t	25.6	20.8	32.12
X_m/W_{ref}	1.50	1.50	2.09
X_m/R_b	0.421	0.360	0.519
$\bar{W}_{av}/H_a$	0.205	0.175	0.166
$\bar{W}_{av}/R_b$	0.286	0.261	0.245
d_t/R_b	0.0100	0.0120	0.0083
d_t/H_a	0.0072	0.0081	0.0056
R_b/H_a	0.716	0.672	0.676

TABLE IV. - SUMMARY DATA FOR TOWER MODELS^a

[Averaged values for outer half of blade.]

(a) MOD-1 tower

Angle, θ , deg	Minimum velocity, $(V_{\min}/V_0)_{av}$	Average velocity, $(V_{av}/V_0)_{av}$	Average defect, $(\Delta V_{\theta}/V_0)_{av}$	Width, $(\delta/R_b)_{av}$
0	0.720	0.837	0.163	0.359
5	.705	.833	.167	.358
10	.707	.830	.170	.373
20	.725	.840	.160	.402
30	.719	.848	.152	.419
45	.684	.857	.143	.432

(b) MOD-0 tower

0	0.657	0.842	0.158	0.324
10	.643	.825	.175	.338
35	.646	.844	.156	.388
^b 40	.626	.842	.158	.360

(c) Eight-leg tower

0	0.748	0.877	0.123	0.342
15	.775	.876	.124	.345
30	.789	.885	.115	.375
45	.747	.895	.105	.373

^aValues listed are probably one significant figure more than is justified by the accuracy.^bIncomplete surveys.

TABLE V. - COMPARISON OF MEAN VALUES OF WAKE

VELOCITY DEFECT AND WIDTH^a

Tower model	Mean average velocity defect ratio, $(\Delta V_{av}/V_0)_{av}$		Mean width ratio, $(\delta/R_b)_{av}$	
	Measuring plane	Blade plane ^b	Measuring plane	Blade plane ^c
MOD-1	0.157	0.201	0.399	0.372
MOD-0	.162	.194	.363	.345
Eight-leg	.117	.163	.359	.325

^aValues listed are probably one significant figure more than is justified by the accuracy.^bEstimated by eq. (4).^cEstimated by eq. (8).

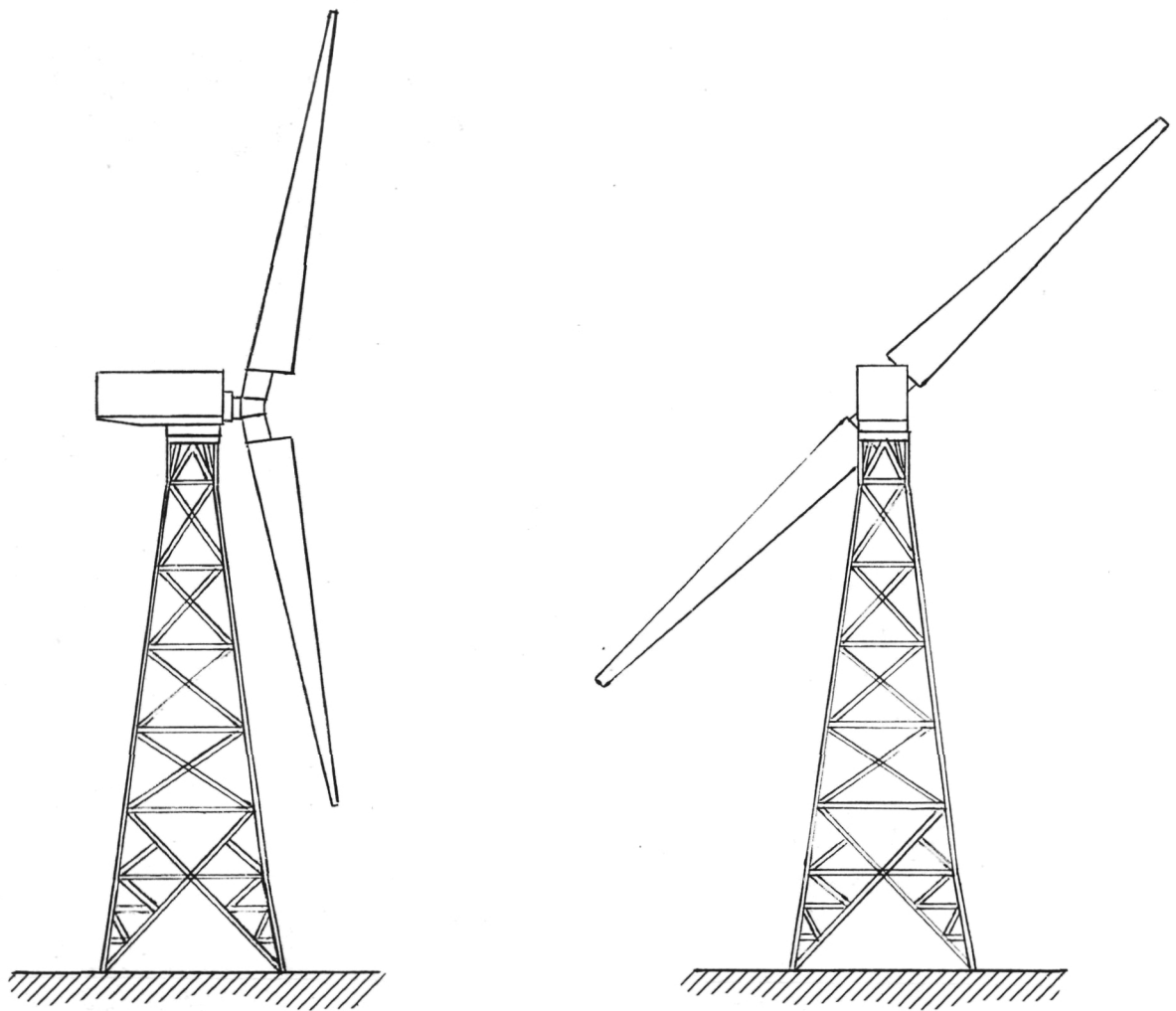


Figure 1. - Sketch of 1800-kilowatt MOD-1 wind turbine preliminary design.

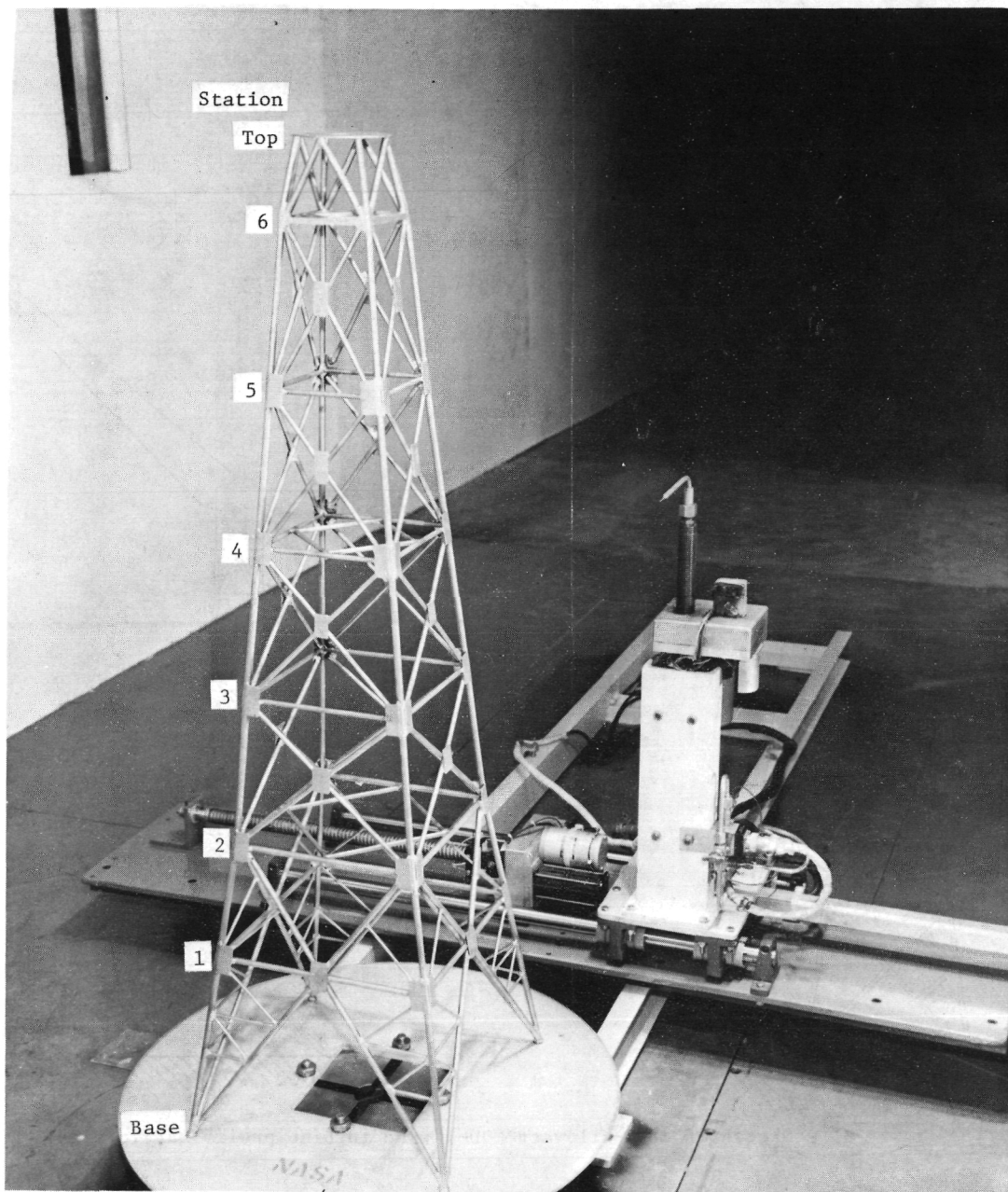
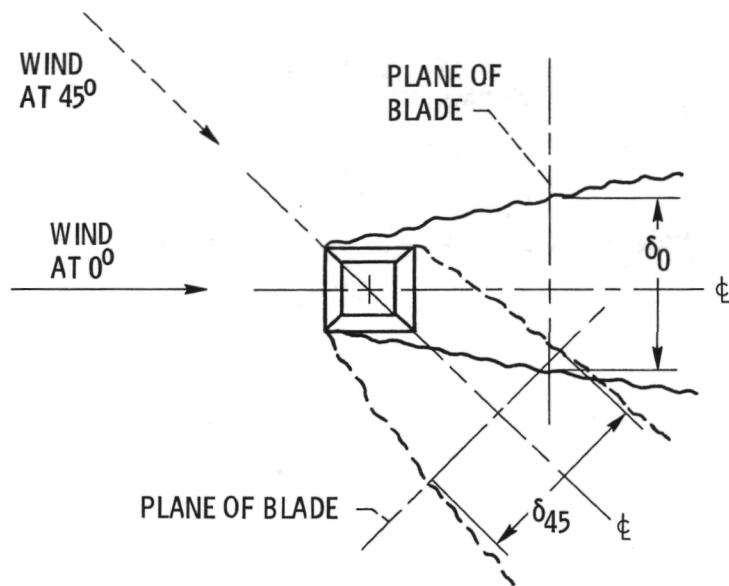
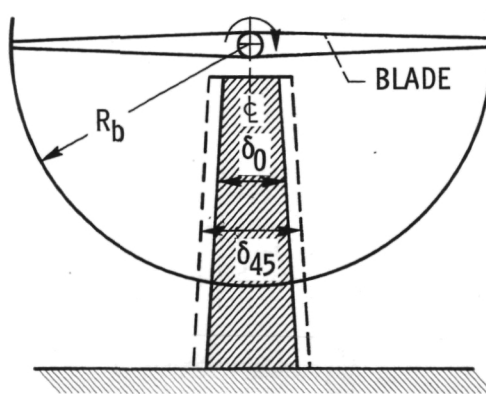


Figure 2. - Photograph of 1/40th-scale model of 1800-kilowatt MOD-1 wind turbine. Model is shown installed in low-speed wind tunnel.

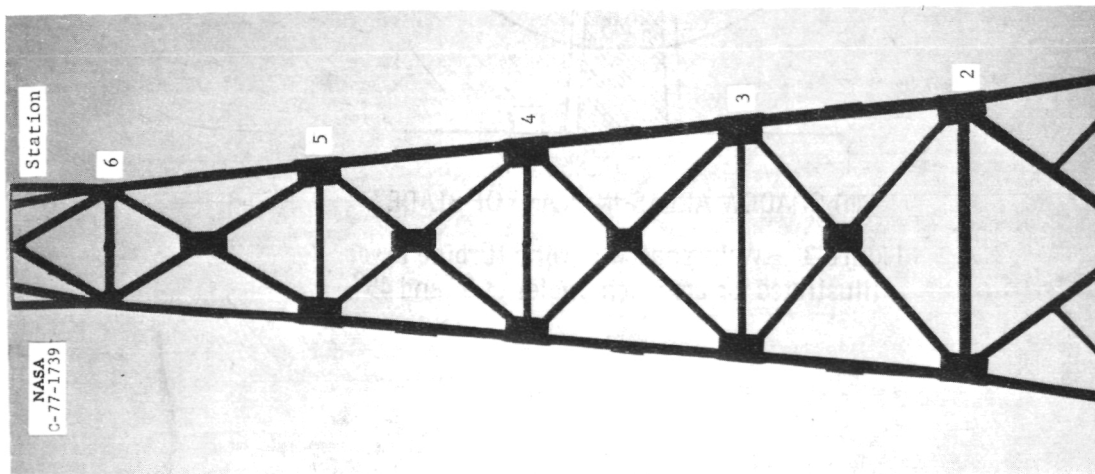


(a) WAKE DEVELOPMENT.

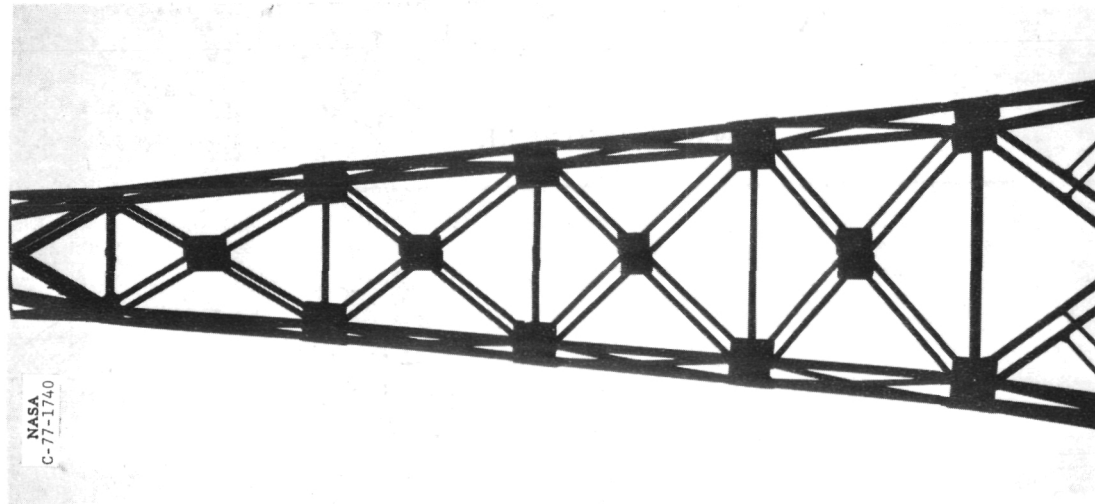


(b) SHADOW AREAS IN PLANE OF BLADE.

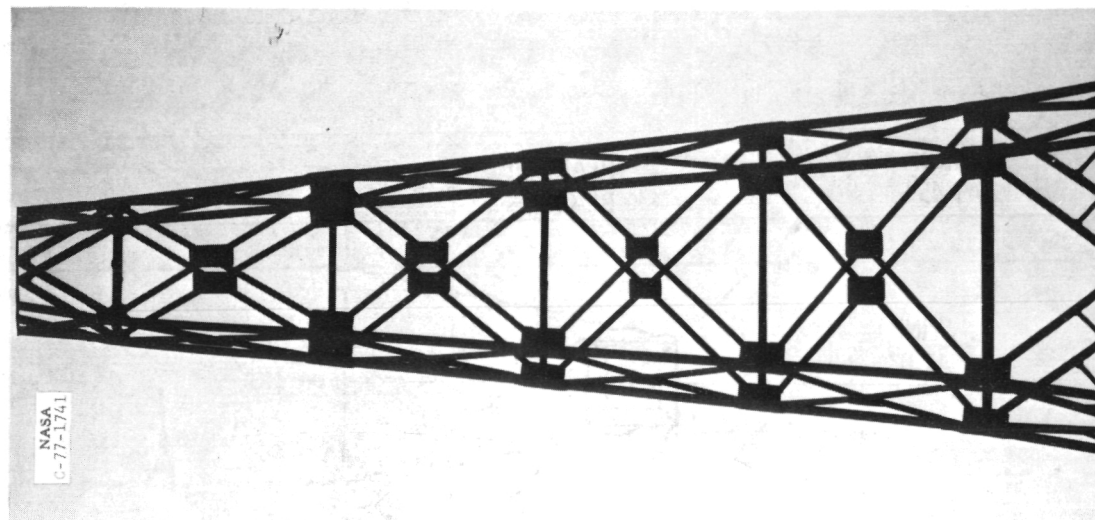
Figure 3. - Wake shadow of wind turbine tower.
Illustrated for approach angles of 0° and 45° .



(a) $\theta = 0^\circ$.



(b) $\theta = 5^\circ$.



(c) $\theta = 10^\circ$.

Figure 4. - Shadow photographs of MOD-1 tower model.

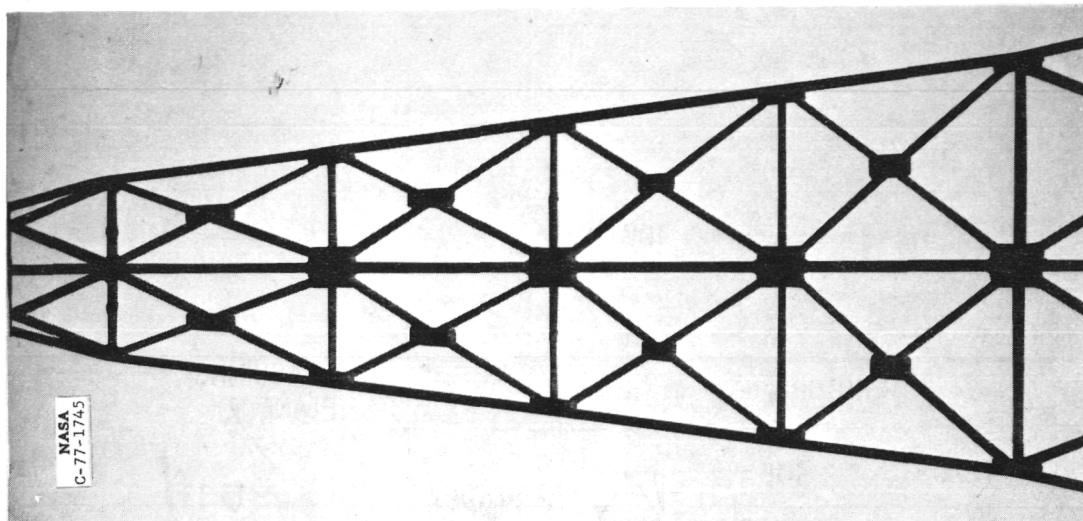
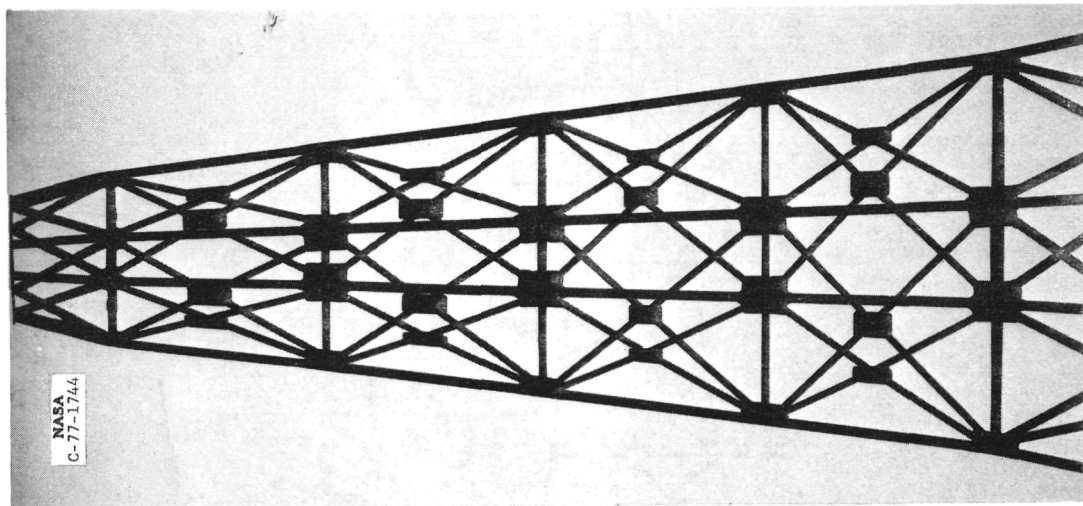
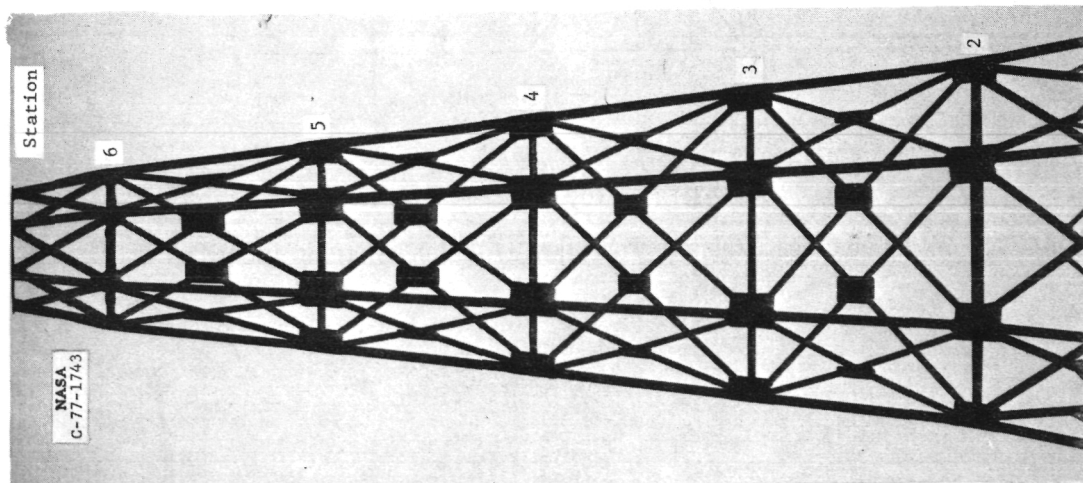
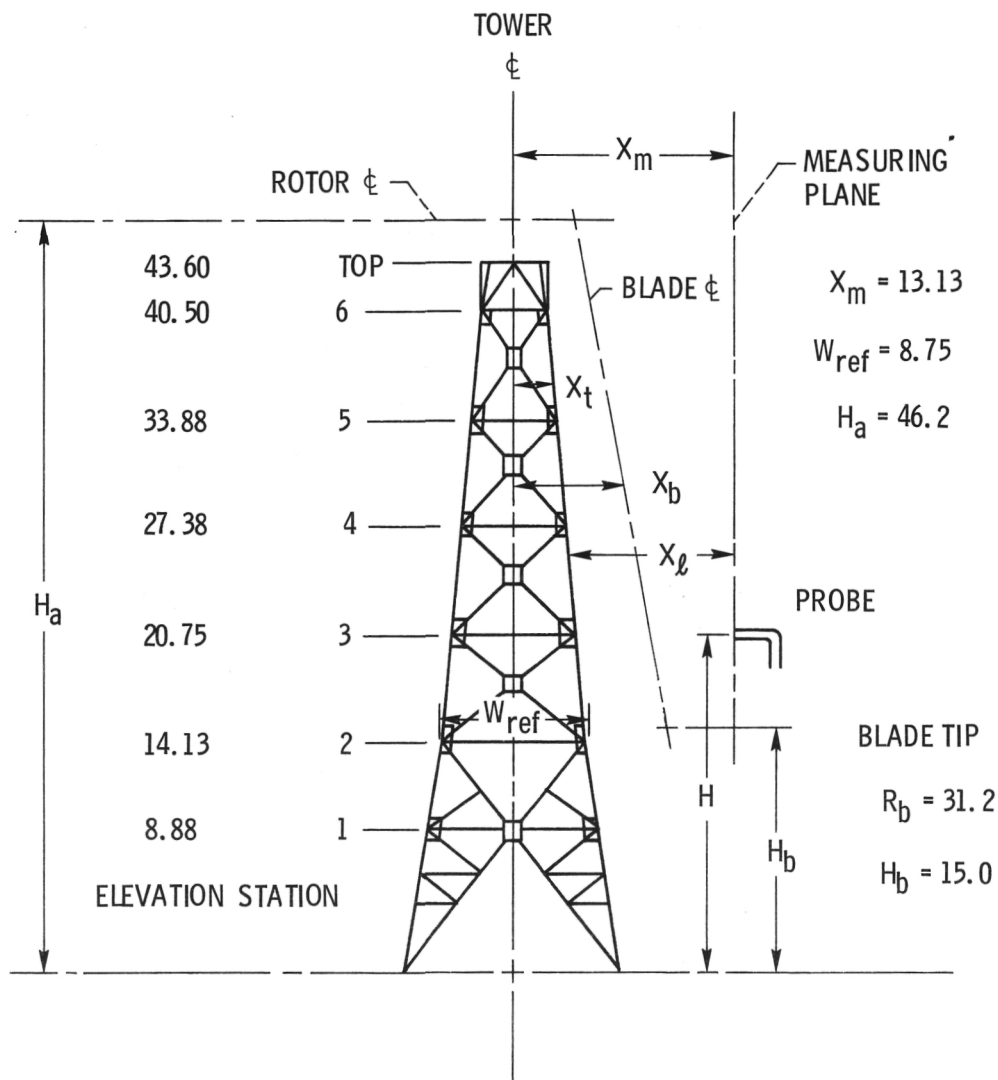
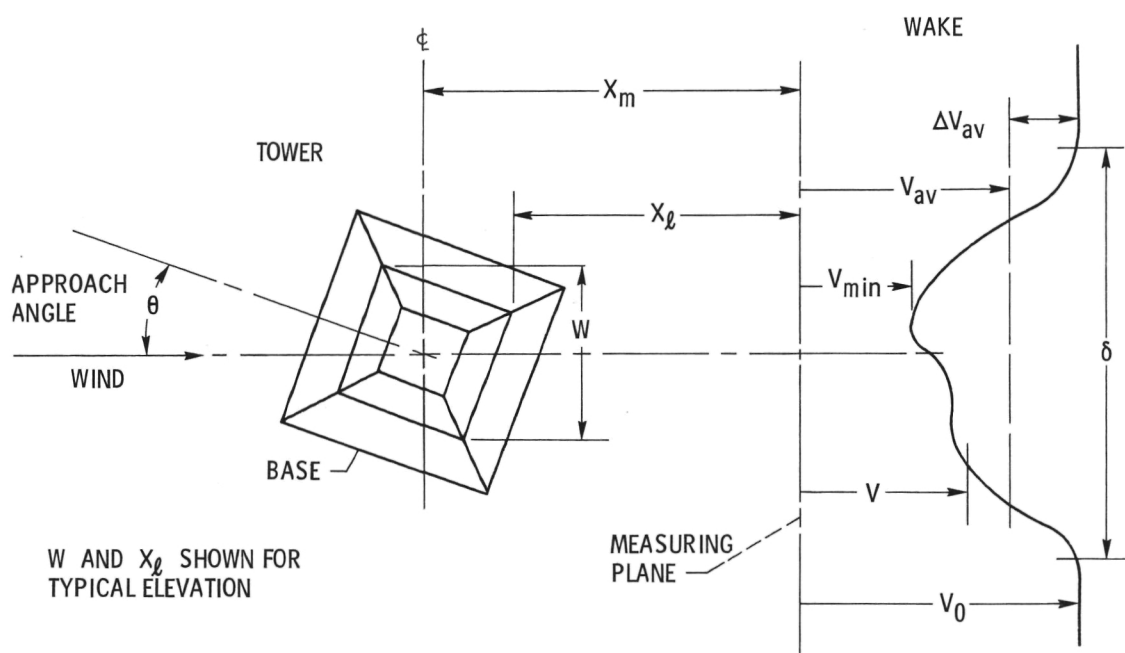


Figure 4. - Concluded.



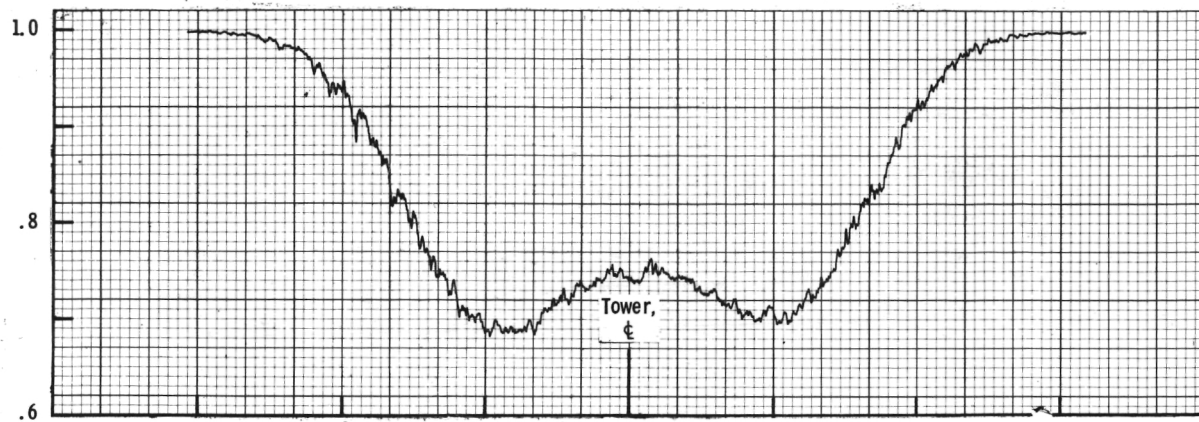
(a) VERTICAL PLANE.

Figure 5. - Model and measurement properties. All dimensions in inches.

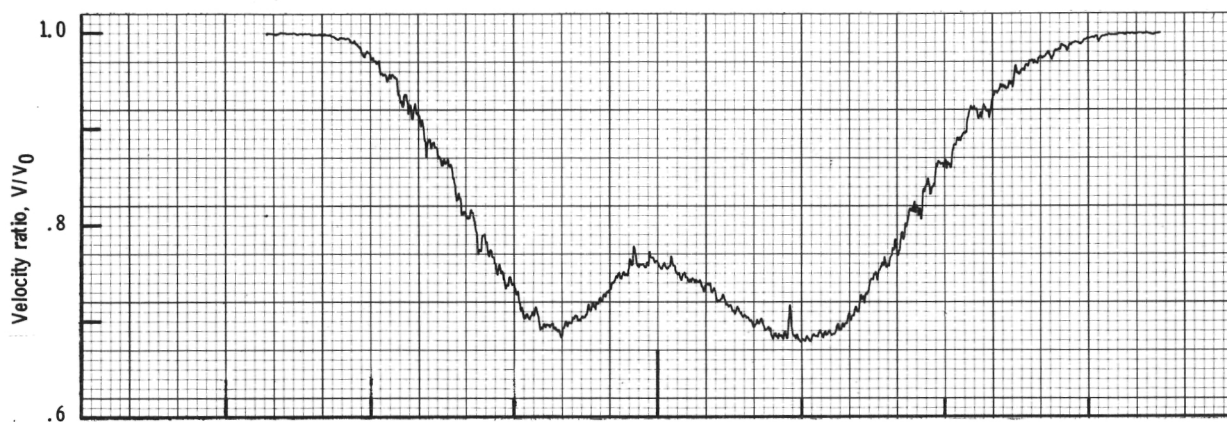


(b) HORIZONTAL PLANE.

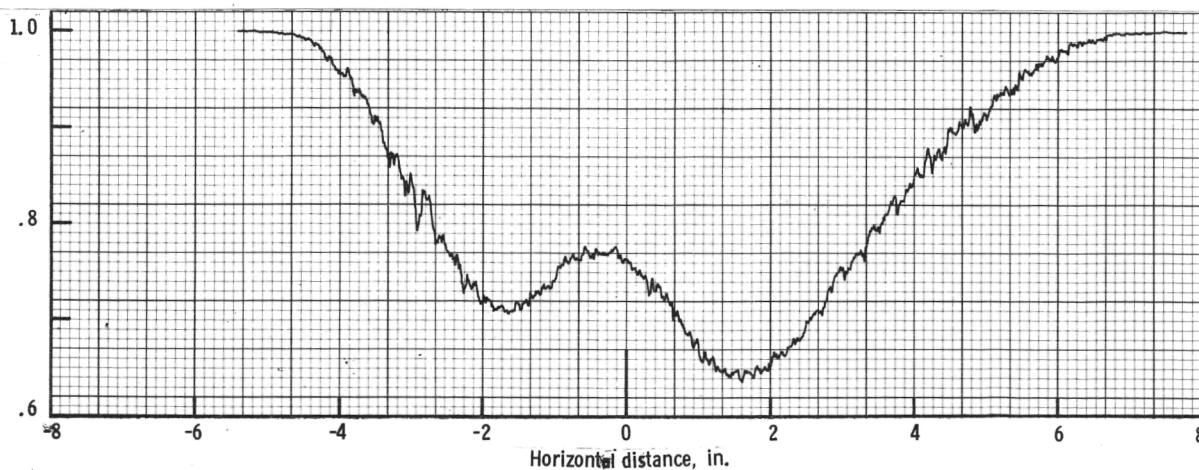
Figure 5. - Concluded.



(a) Wind approach angle, $\theta = 0^\circ$.

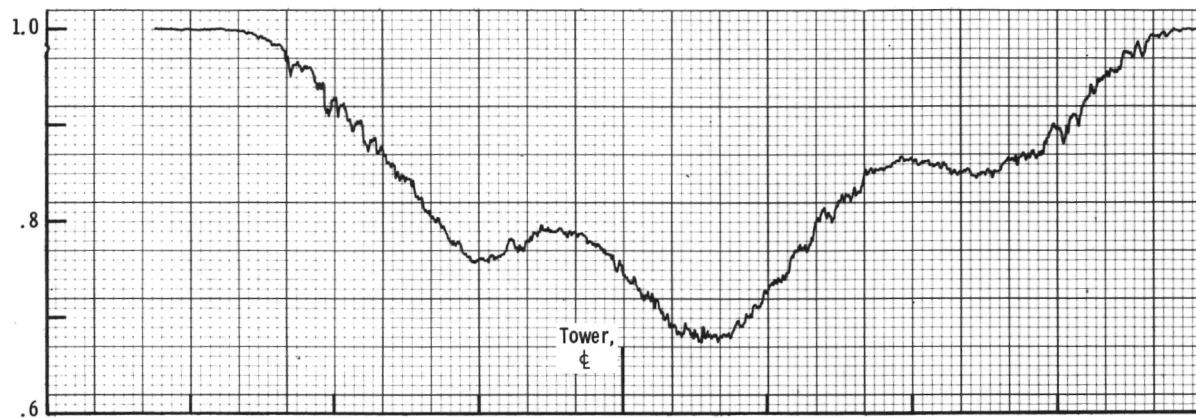


(b) Wind approach angle, $\theta = 5^\circ$.

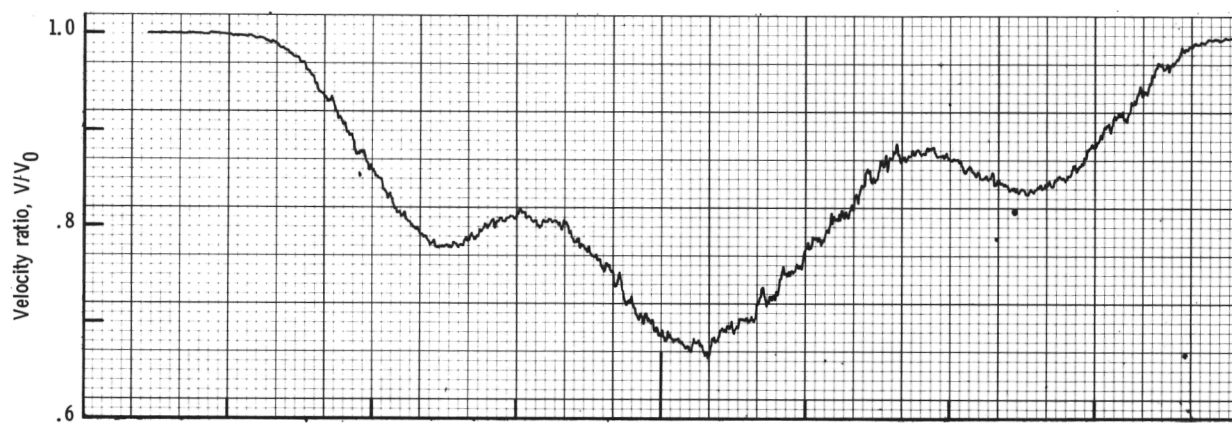


(c) Wind approach angle, $\theta = 10^\circ$.

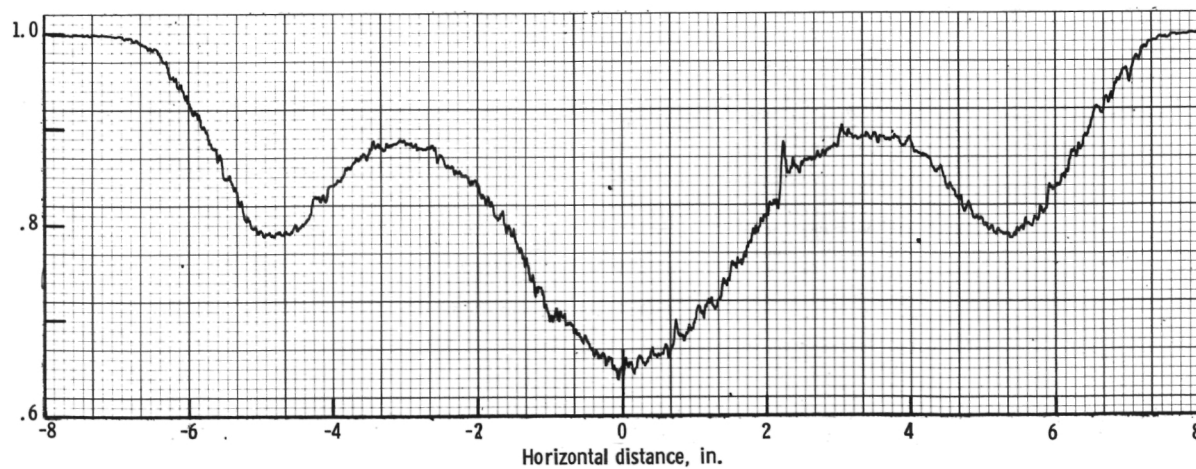
Figure 6. - Wind speed profiles in the wake of the MOD-1 model tower at elevation, $H = 20.95$ in.



(d) Wind approach angle, $\theta = 20^\circ$.

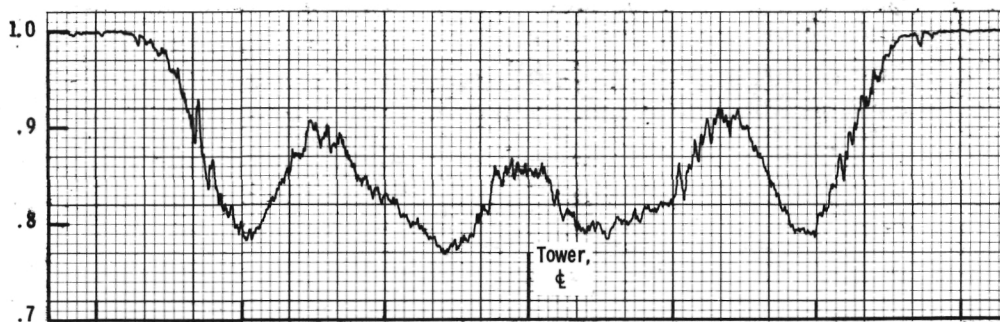


(e) Wind approach angle, $\theta = 30^\circ$.

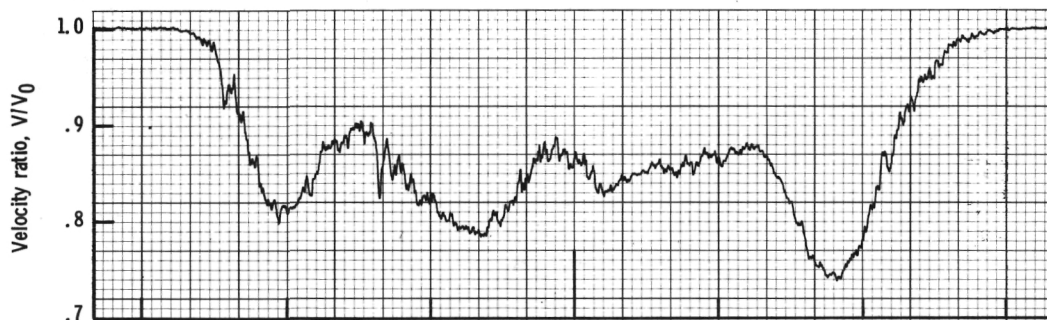


(f) Wind approach angle, $\theta = 45^\circ$.

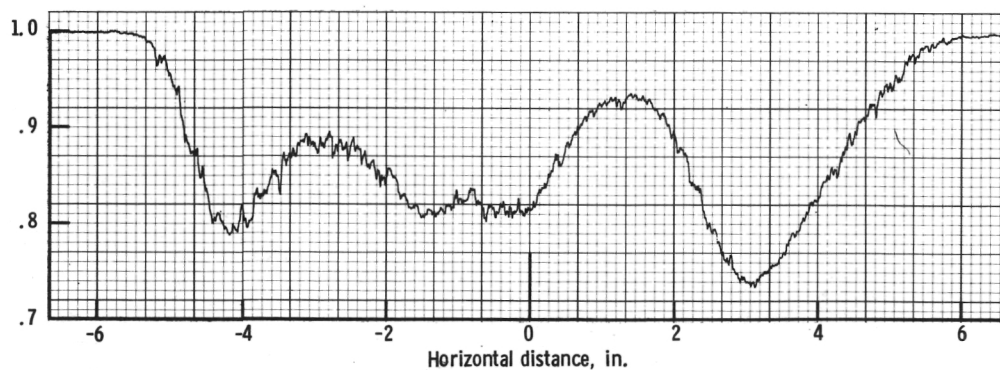
Figure 6. - Concluded.



(a) Wind approach angle, $\theta = 0^\circ$.

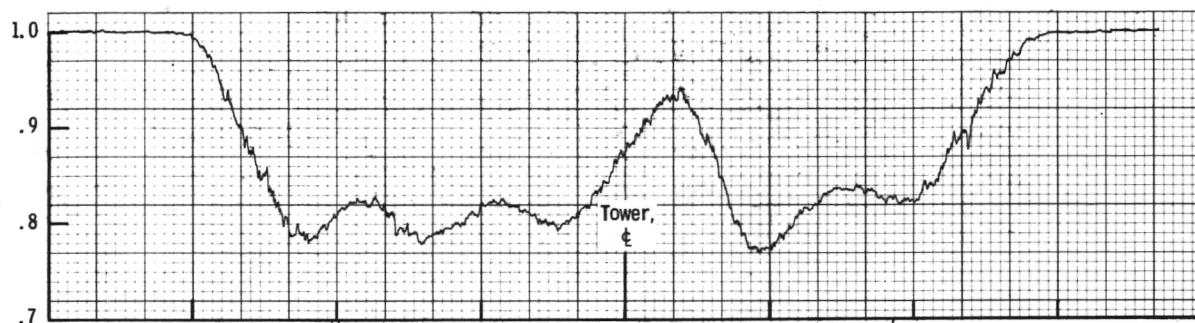


(b) Wind approach angle, $\theta = 5^\circ$.

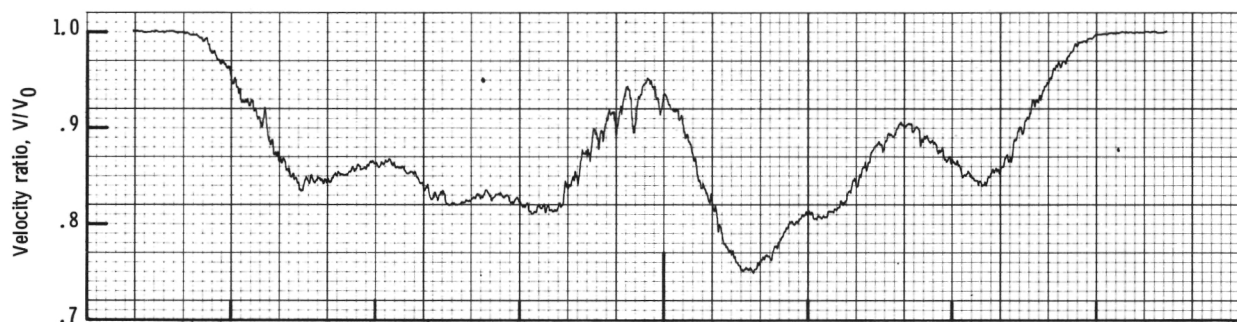


(c) Wind approach angle, $\theta = 10^\circ$.

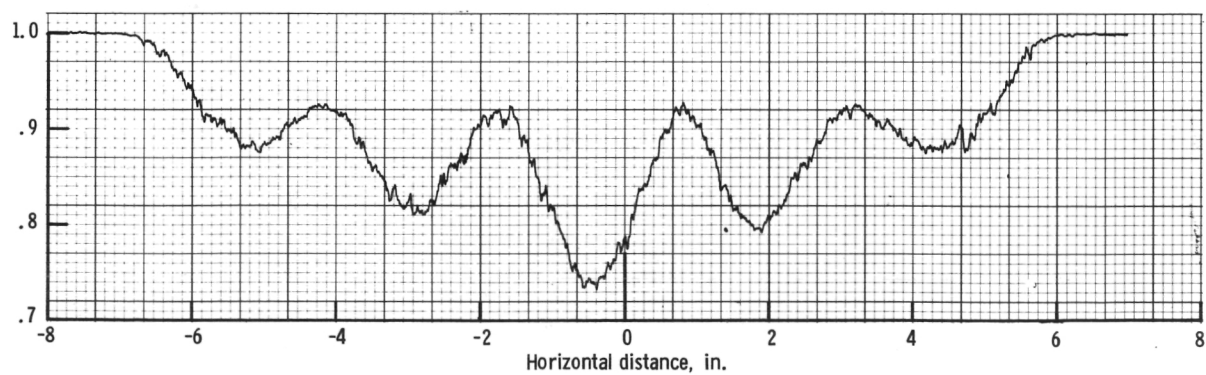
Figure 7. - Wind speed profiles in the wake of the MOD-1 model tower at elevation, $H = 24.55$ in.



(d) Wind approach angle, $\theta = 20^\circ$.



(e) Wind approach angle, $\theta = 30^\circ$.



(f) Wind approach angle, $\theta = 45^\circ$.

Figure 7. - Concluded.

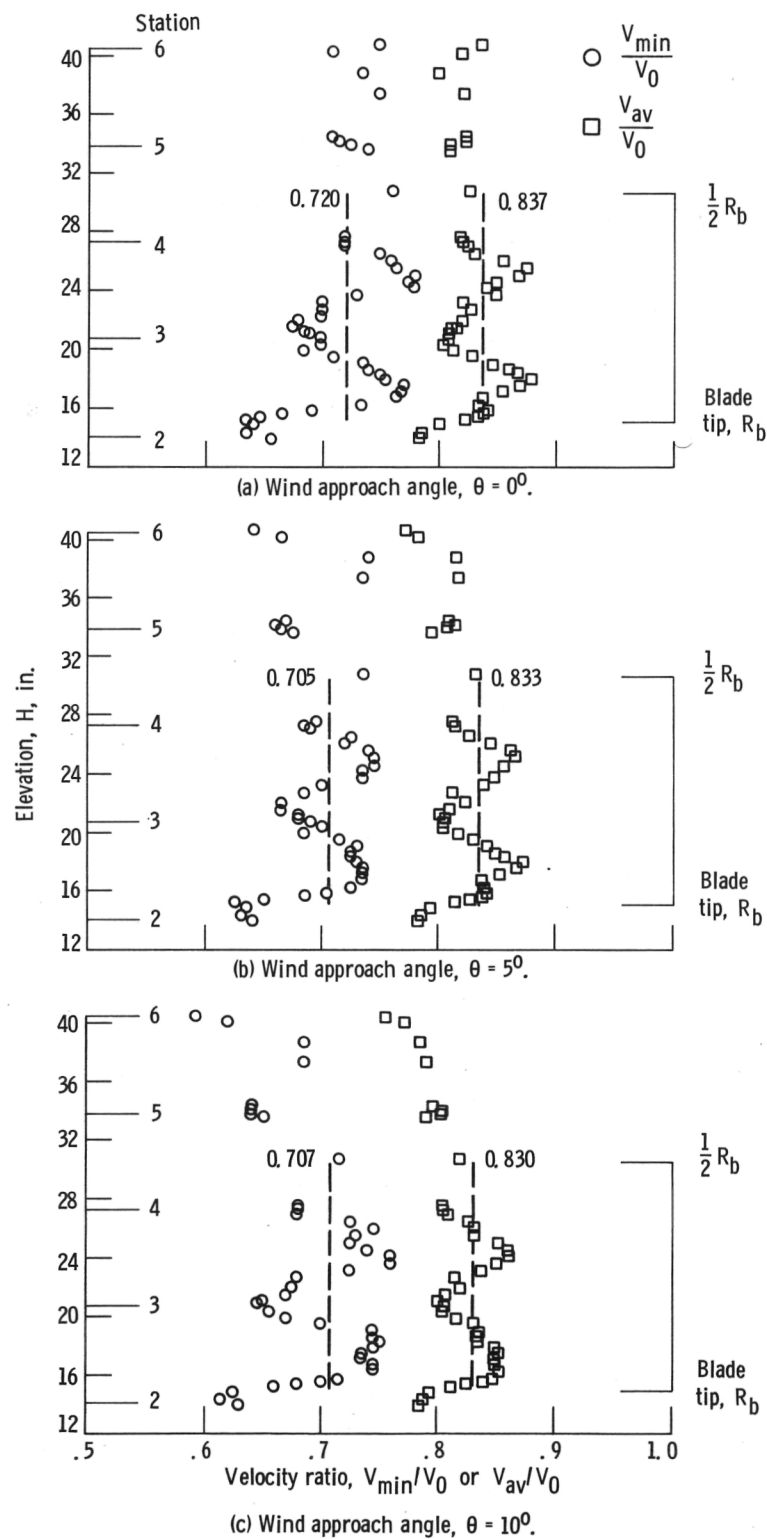


Figure 8. - Wake minimum and average velocity ratios for MOD-1 tower model.

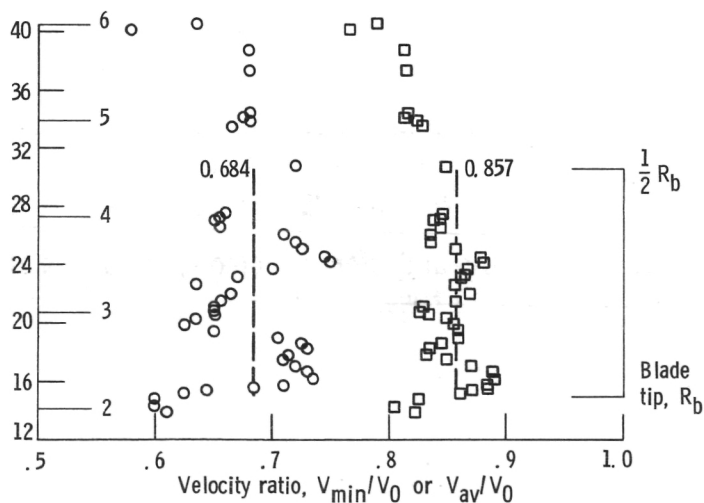
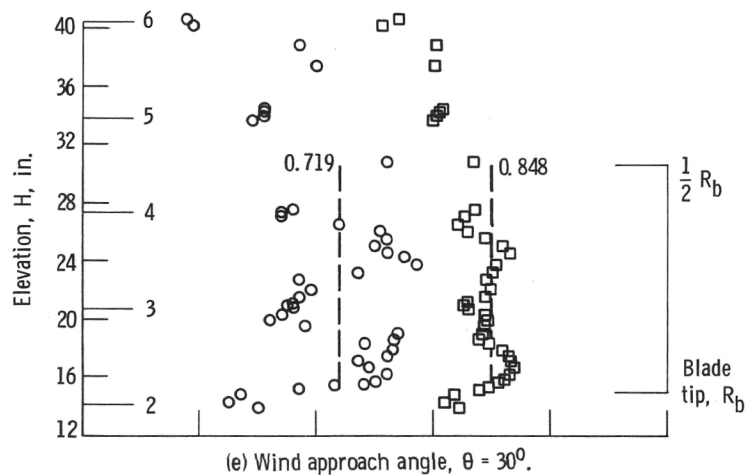
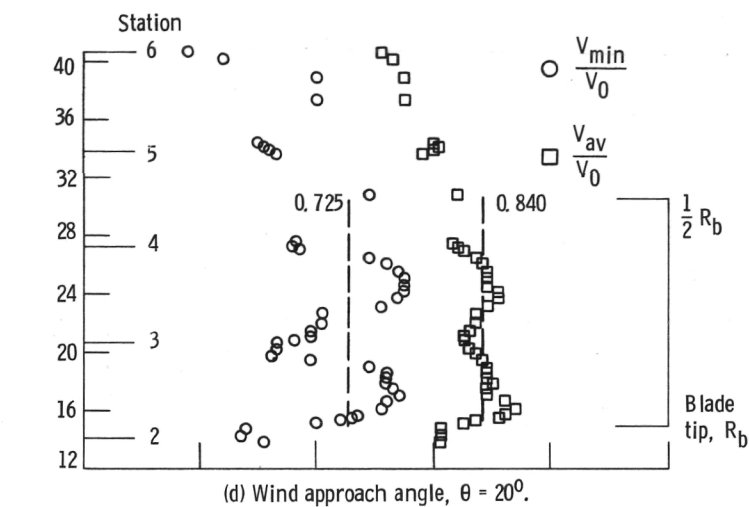


Figure 8. - Concluded.

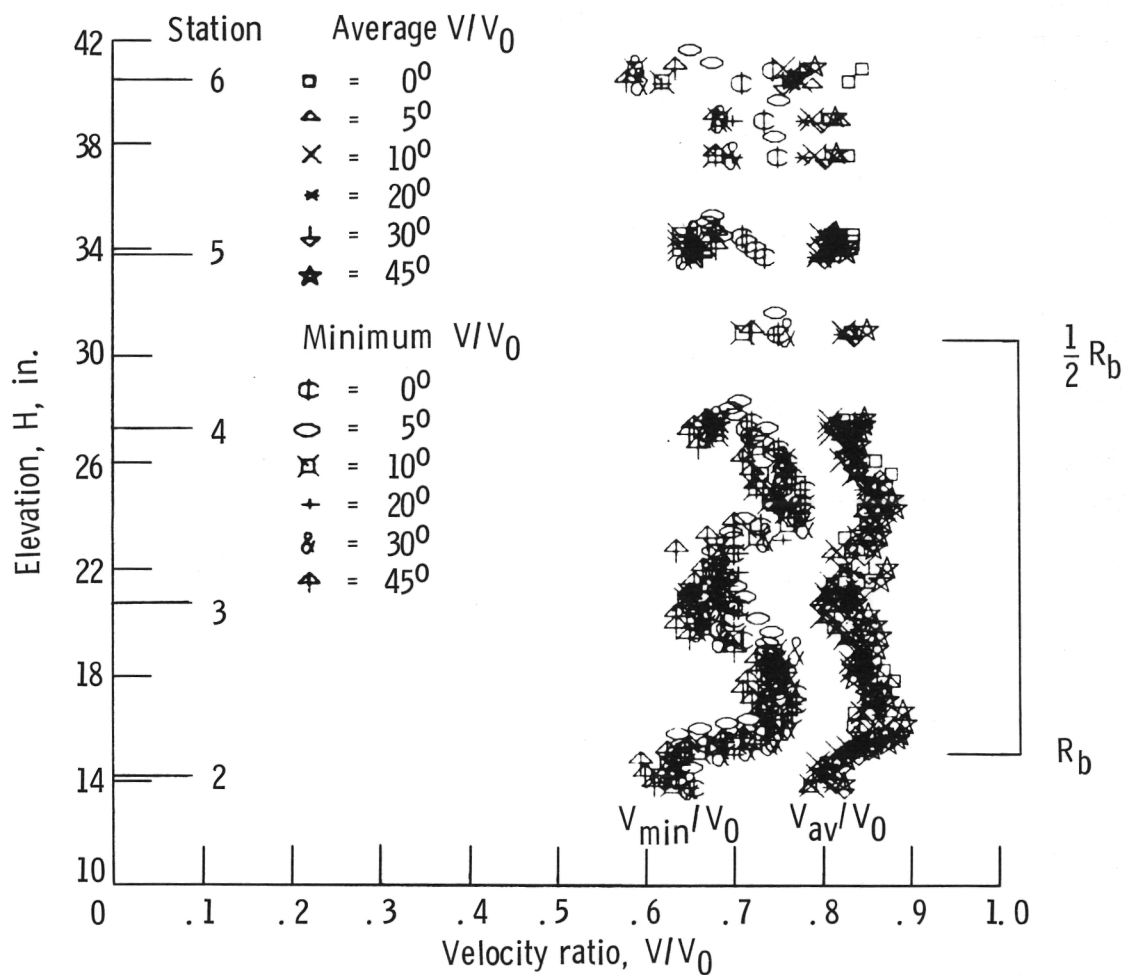


Figure 9. - Wake minimum and average velocity ratios for all wind approach angles for MOD-1 tower model.

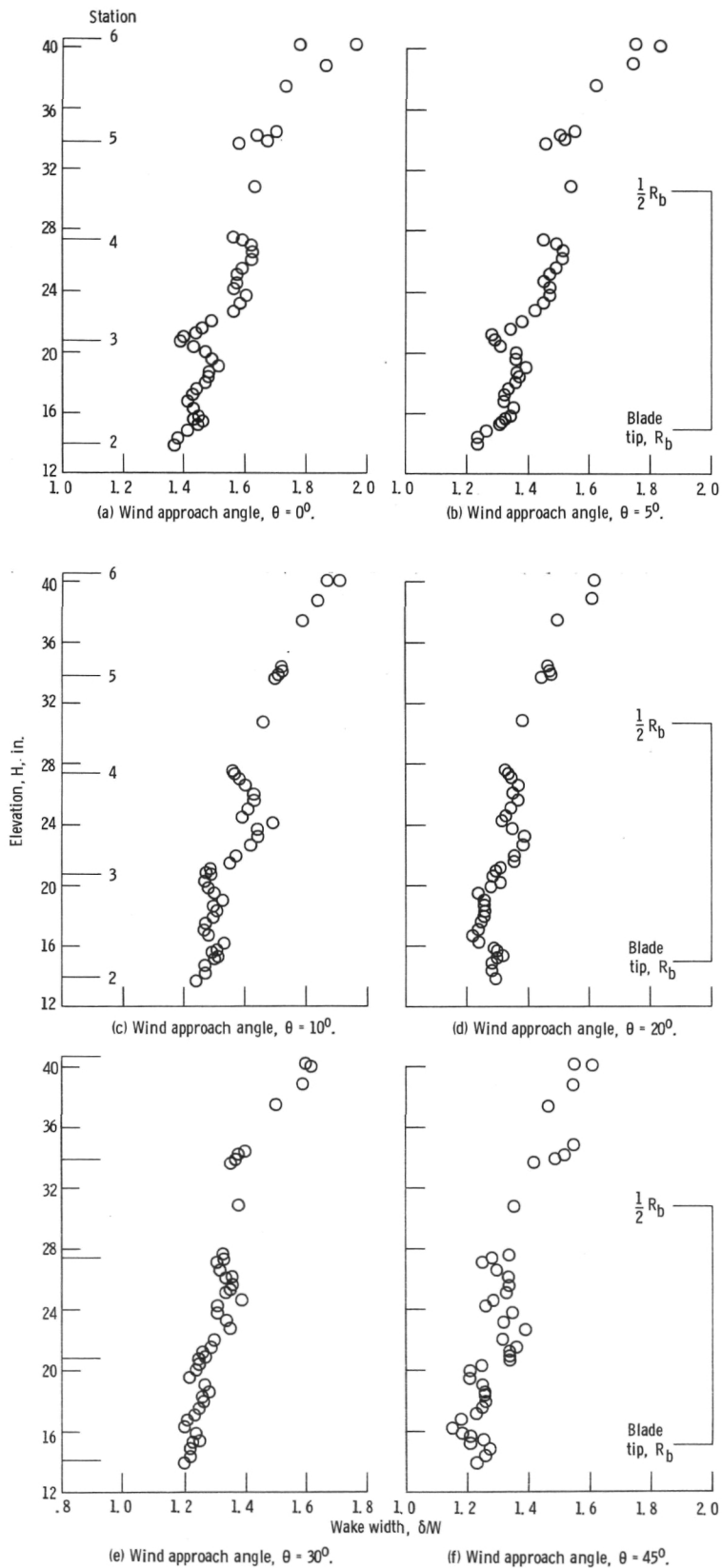


Figure 10. - Ratio of wake width to projected tower width for MOD-1 tower model.

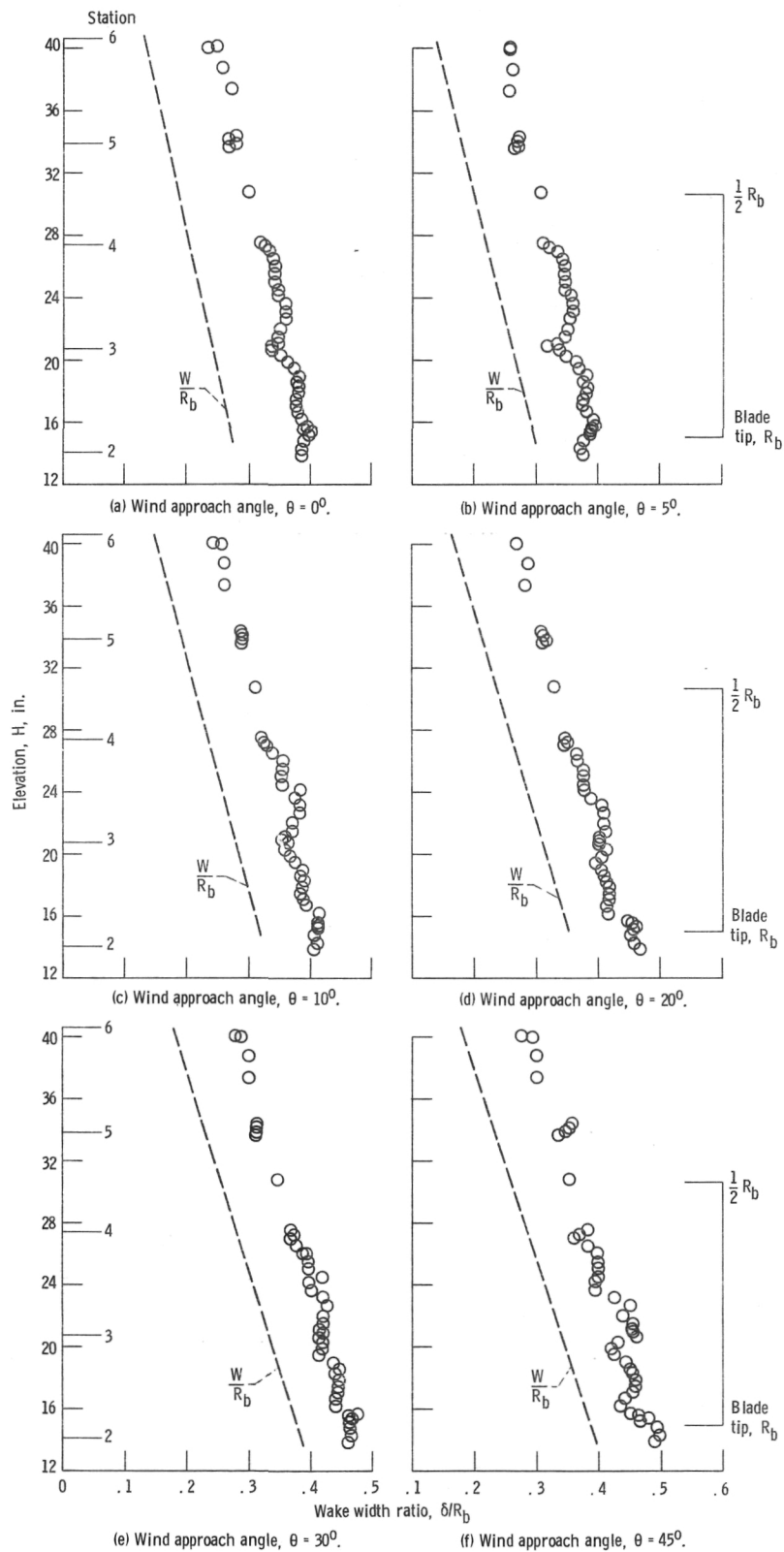
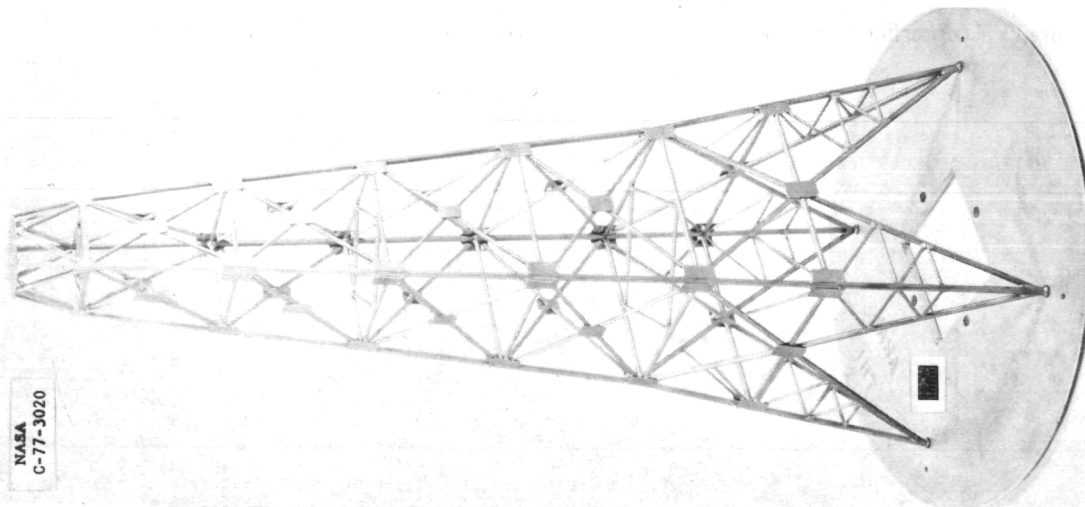
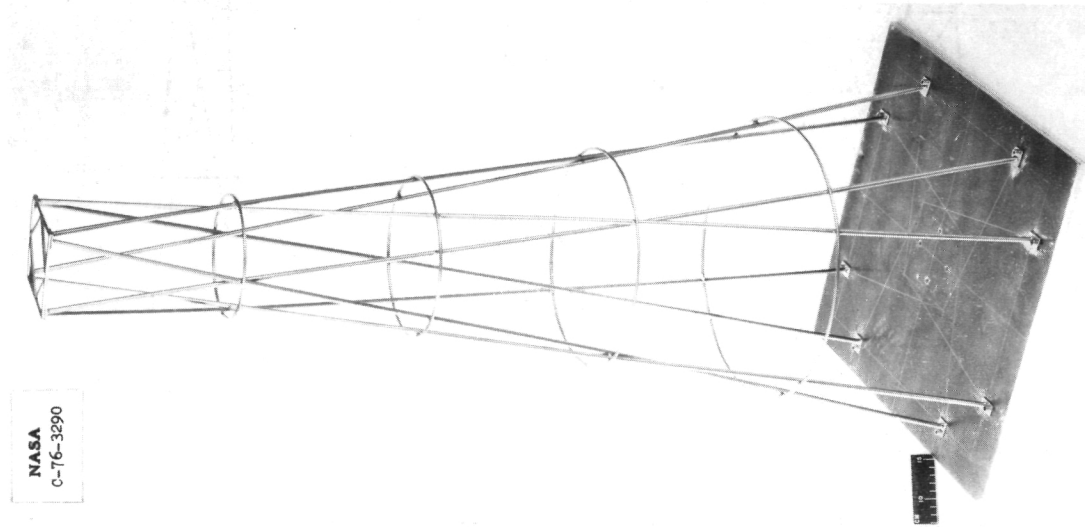


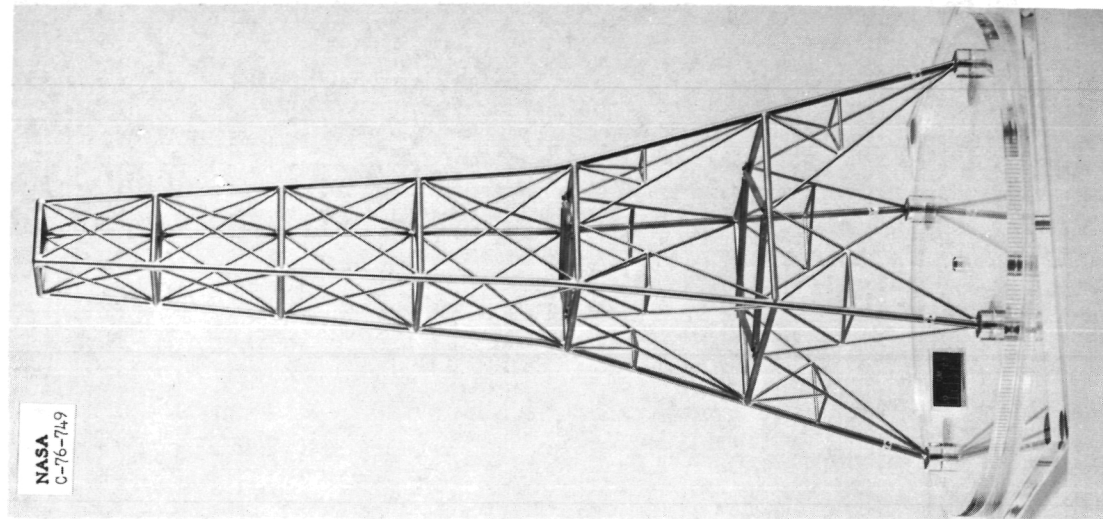
Figure 11. - Ratio of wake width to blade radius for MOD-1 tower model.



(a) MOD-1 (1/40th scale).



(b) Eight-leg (1/25th scale).



(c) MOD-0 (1/48th scale).

Figure 12. - Tower models constructed with tubular elements.

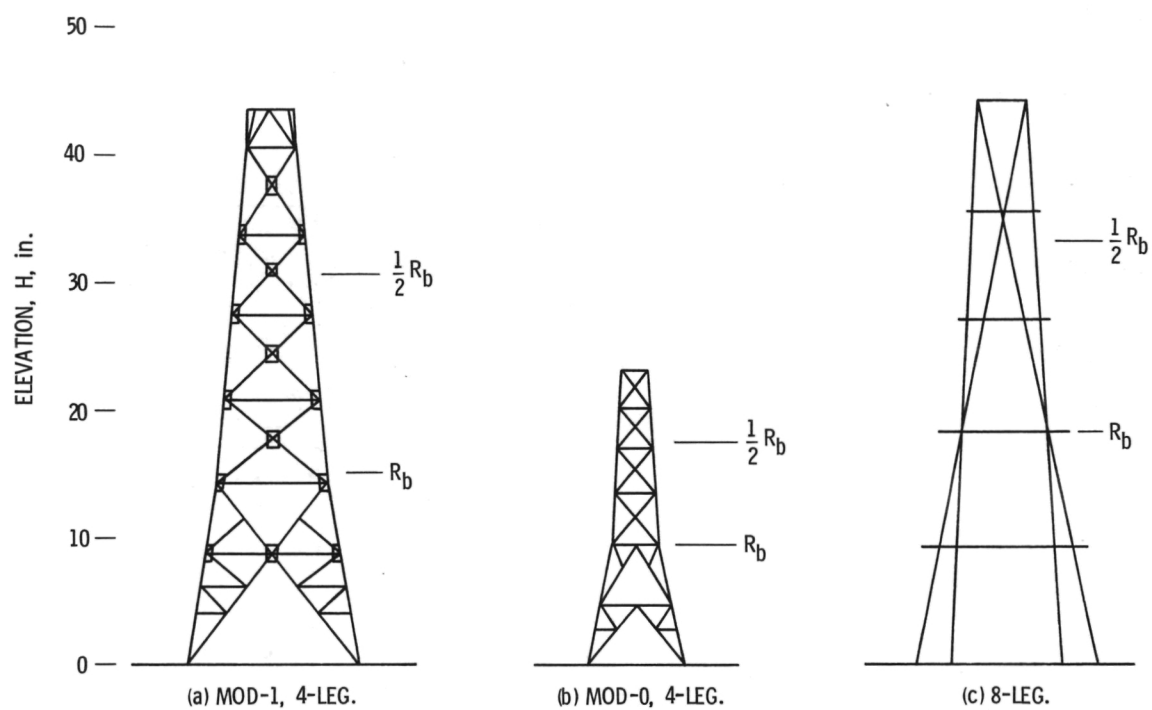


Figure 13. - Comparison of model towers constructed with tubular elements for wind approach angle, $\theta = 0^\circ$.

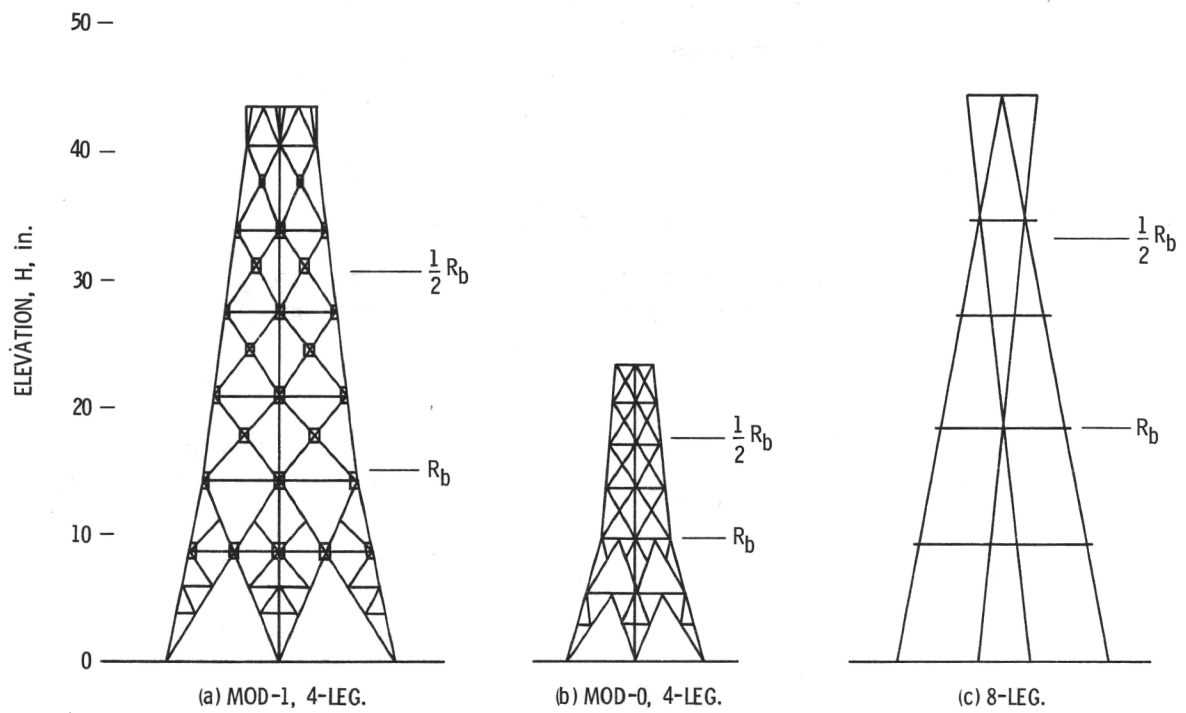
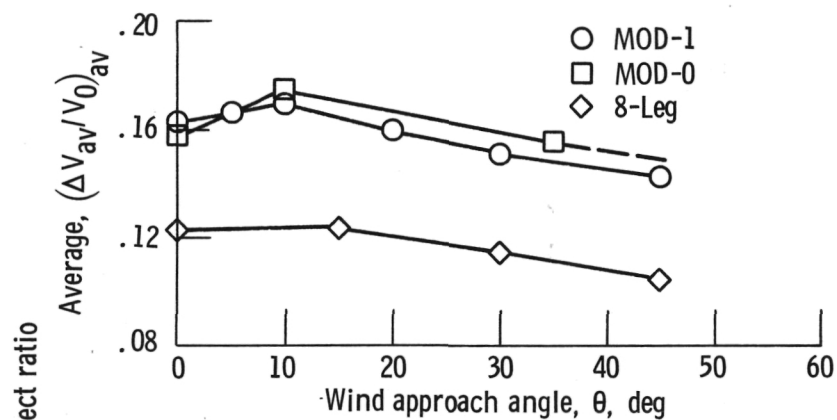
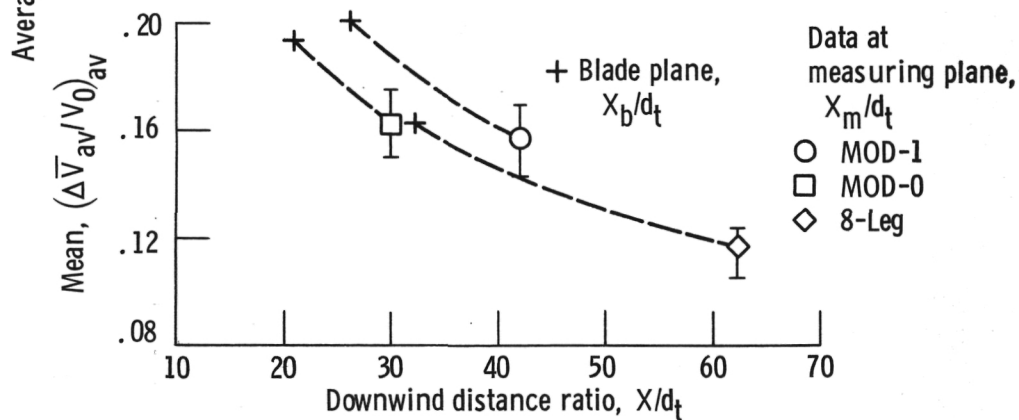


Figure 14. - Comparison of model towers constructed with tubular elements for wind approach angle, $\theta = 45^\circ$.

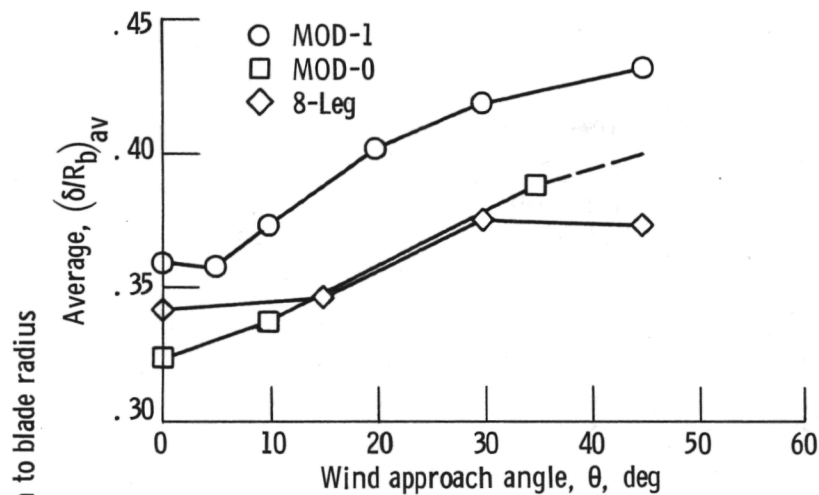


(a) Variation with wind approach angle at the measuring plane. Average values for outer half of rotor blade.

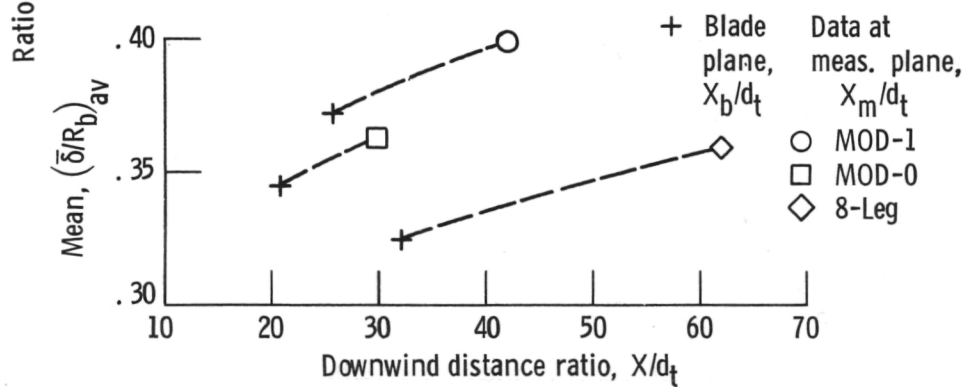


(b) Theoretical variation with distance from tower axis. Mean values for $0^\circ \leq \theta \leq 45^\circ$.

Figure 15. - Comparison of wake average velocity defect for several tower models.



(a) Variation with wind approach angle at the measuring plane. Average values for outer half of rotor blade.



(b) Theoretical variation with distance from tower axis. Mean values for $0^\circ \leq \theta \leq 45^\circ$.

Figure 16. - Comparison of wake width for several tower models.

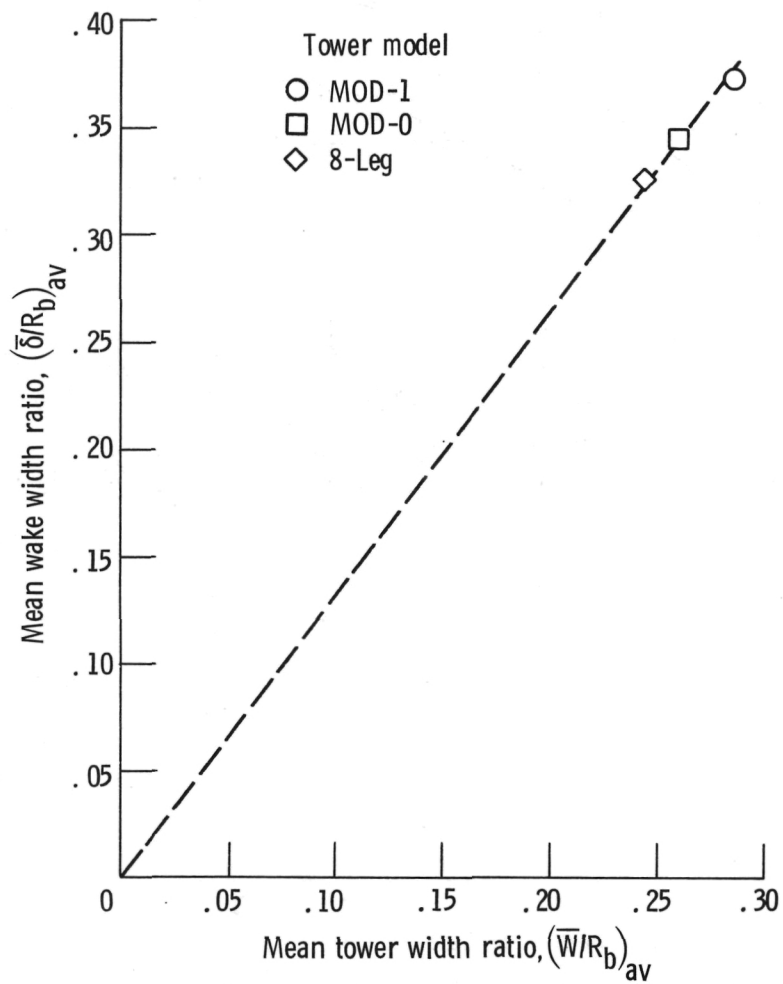
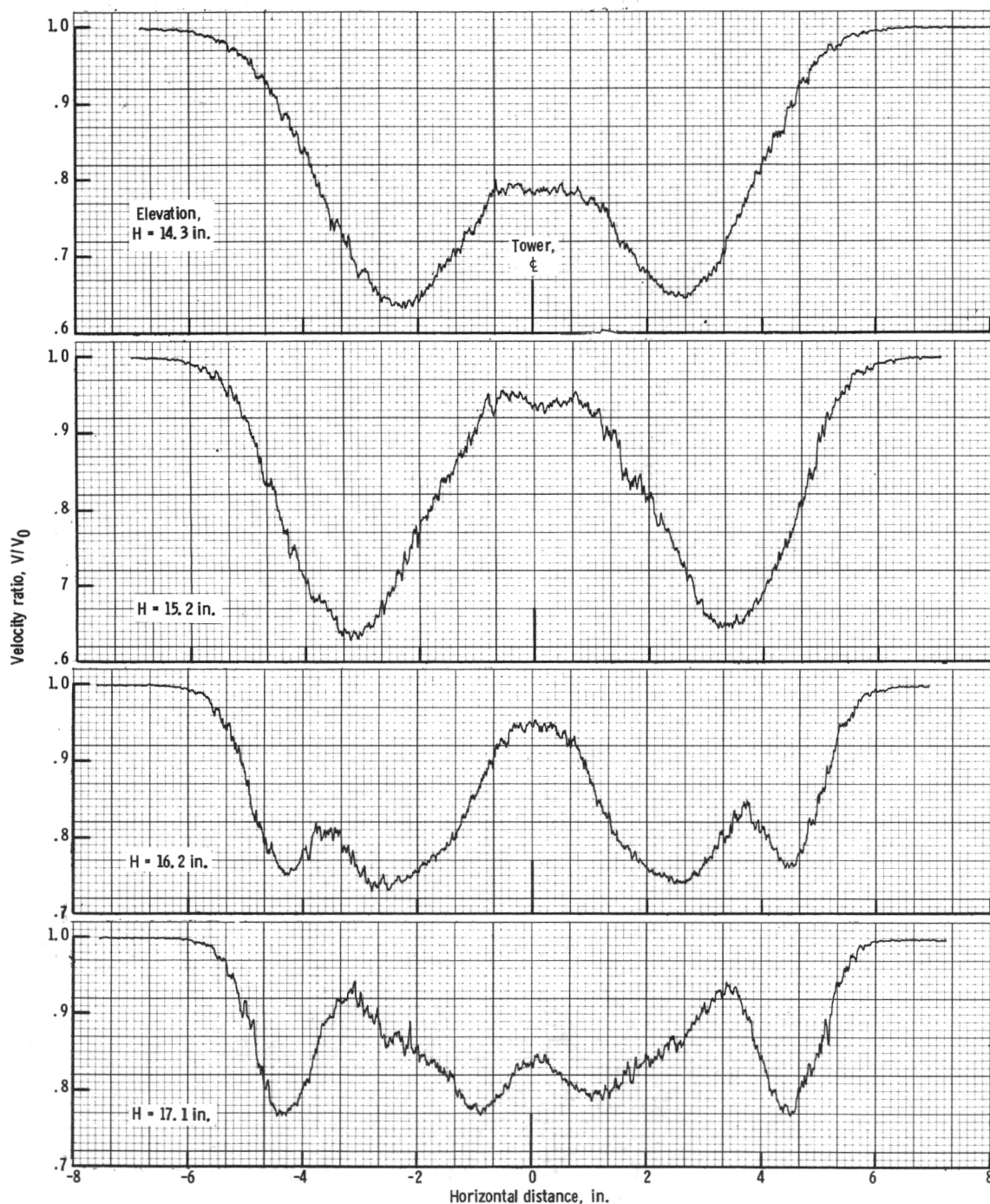
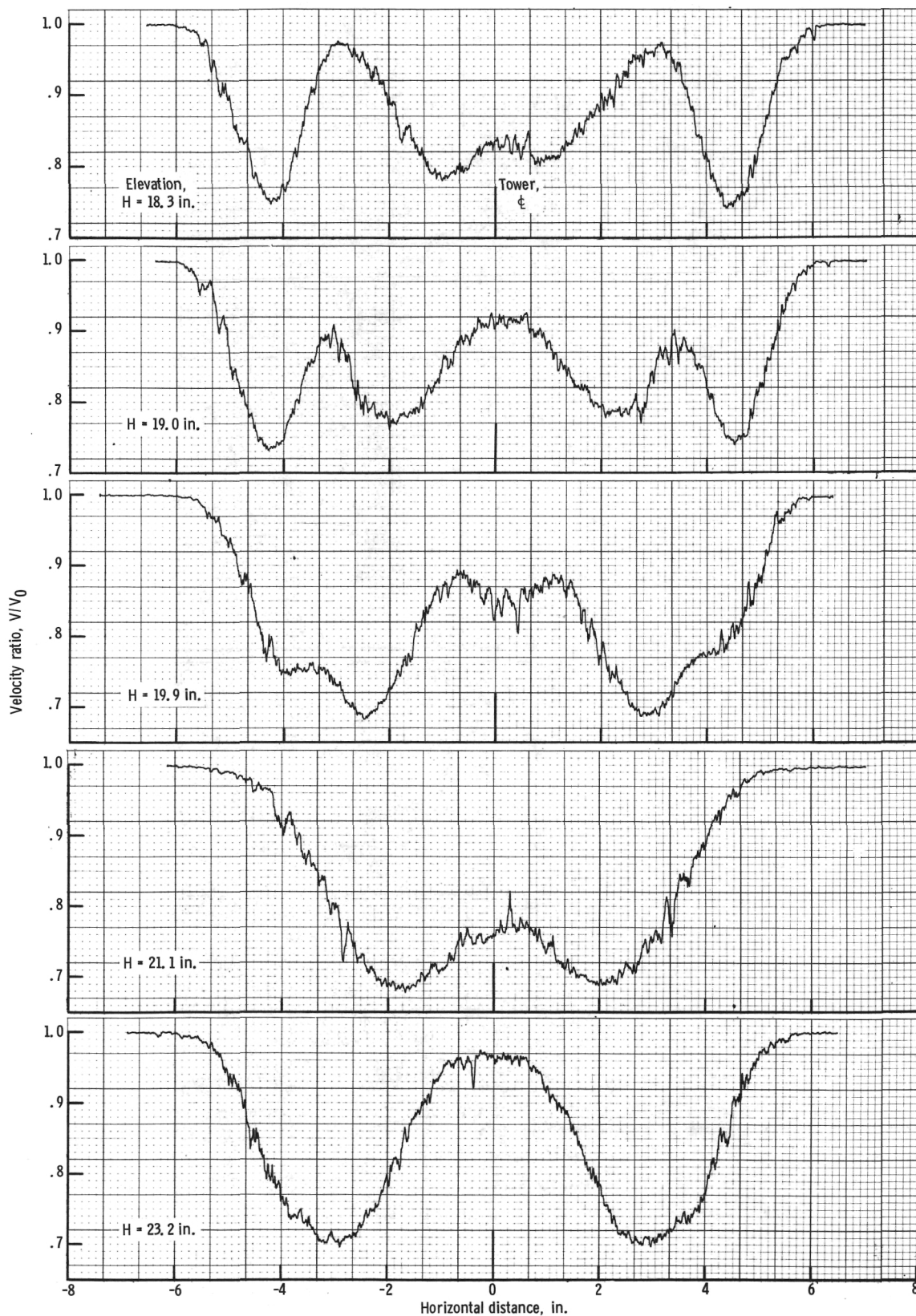


Figure 17. - Correlation of mean wake width at the rotor blade with mean tower projected width.



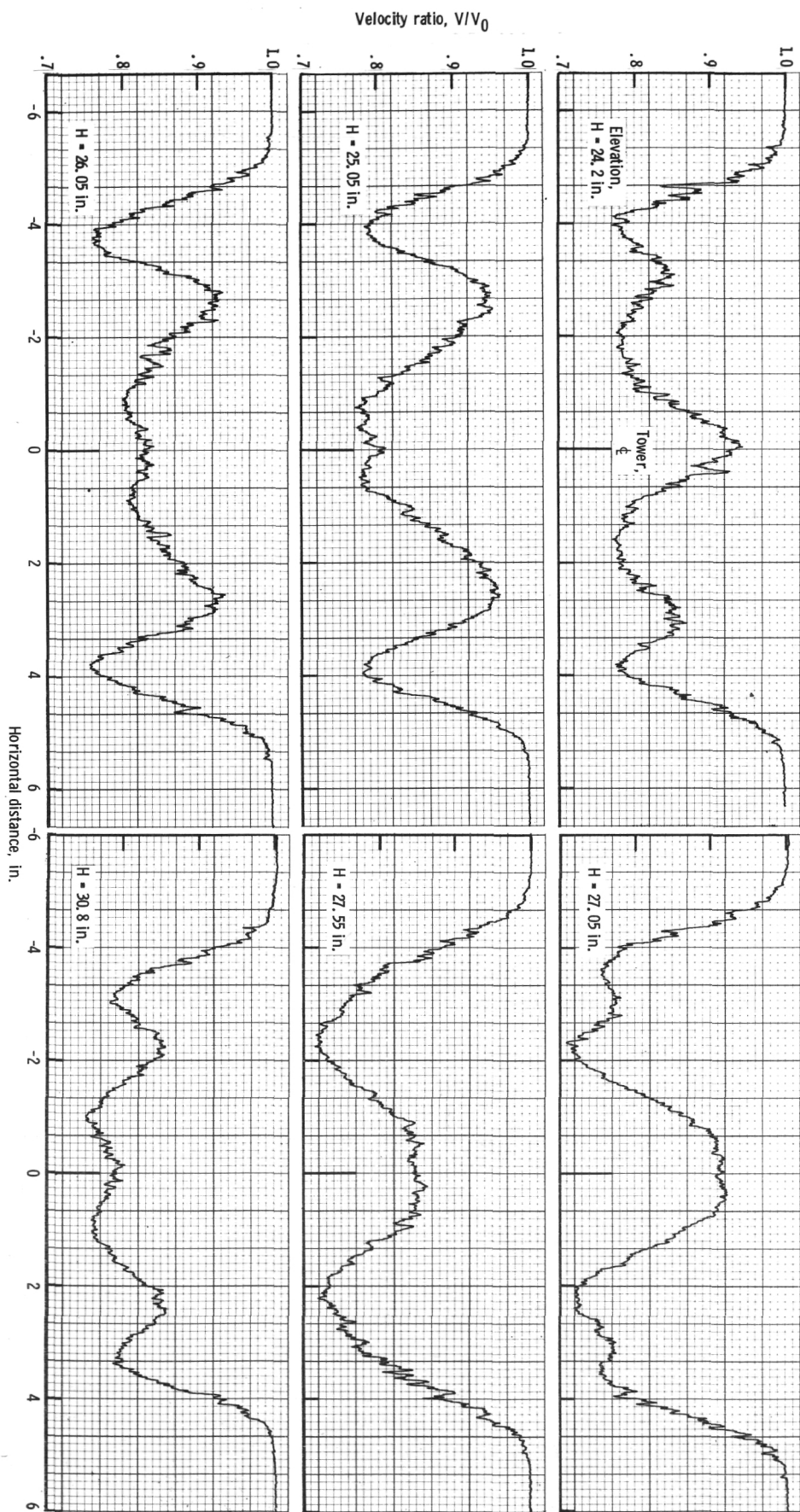
(a) Wind approach angle, $\phi = 0^\circ$.

Figure 18. - Wind speed profiles in the wake of the MOD-1 model tower - variation with elevation.

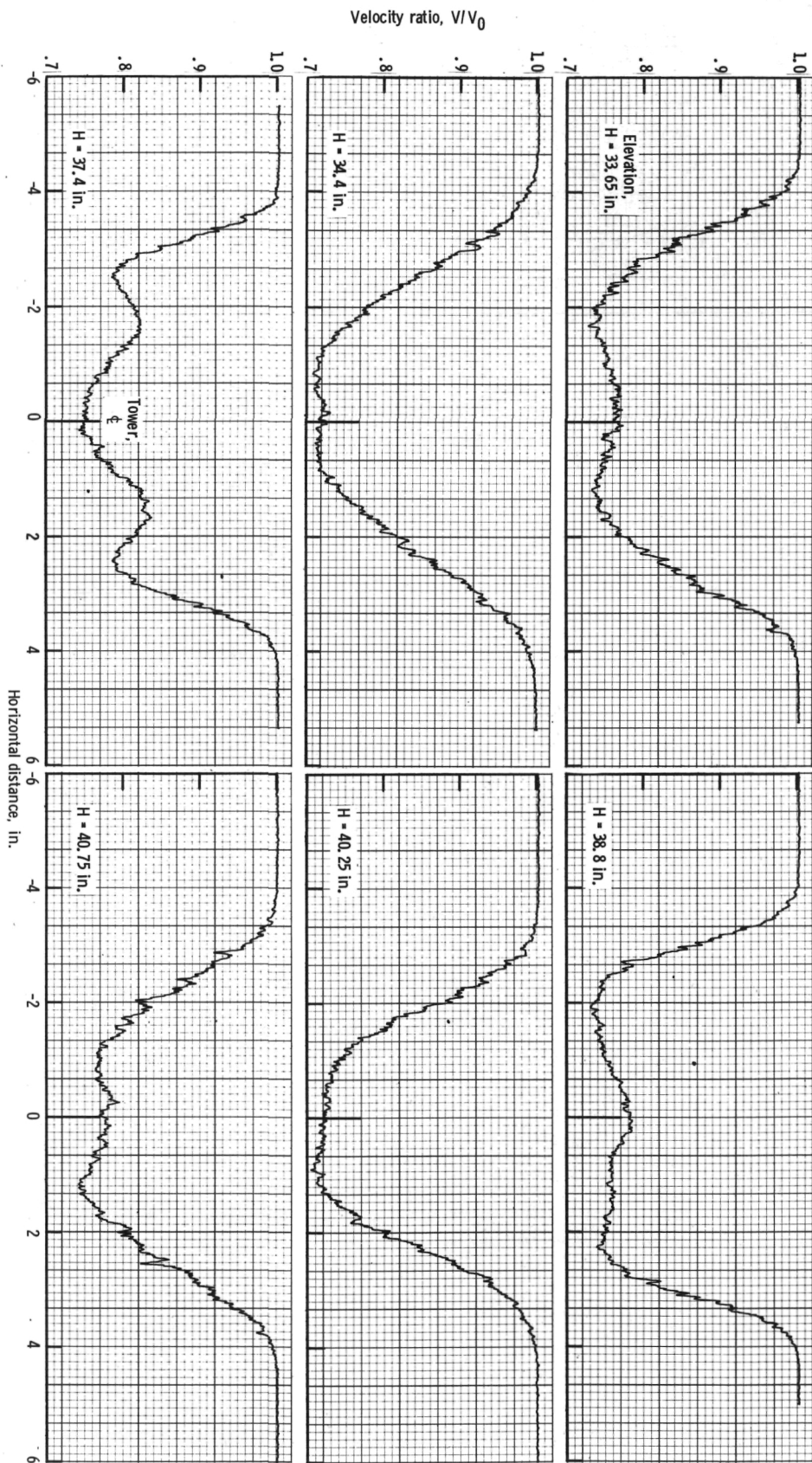


(a) Continued.

Figure 18. - Continued.

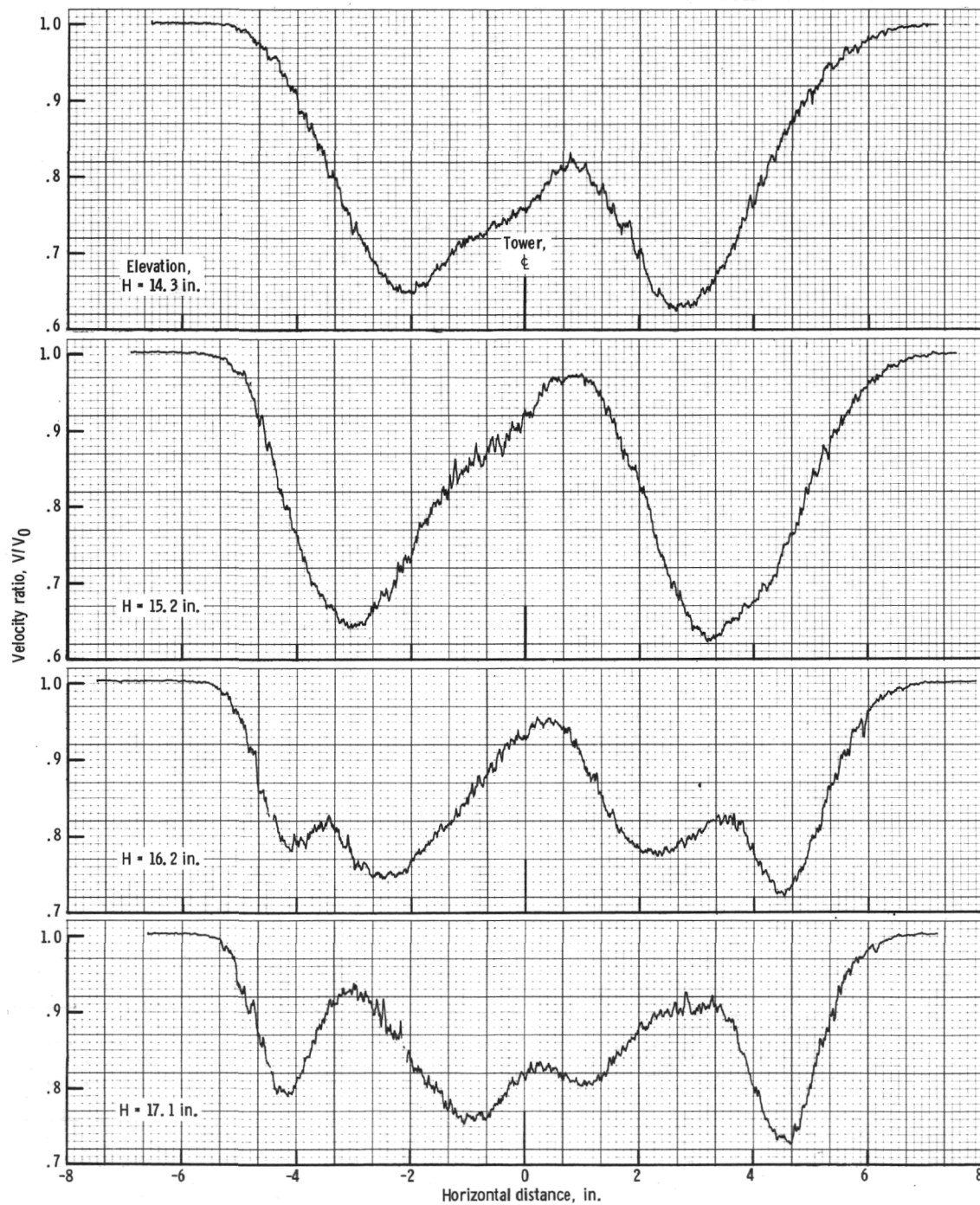


(a) Continued.
Figure 18. - Continued.



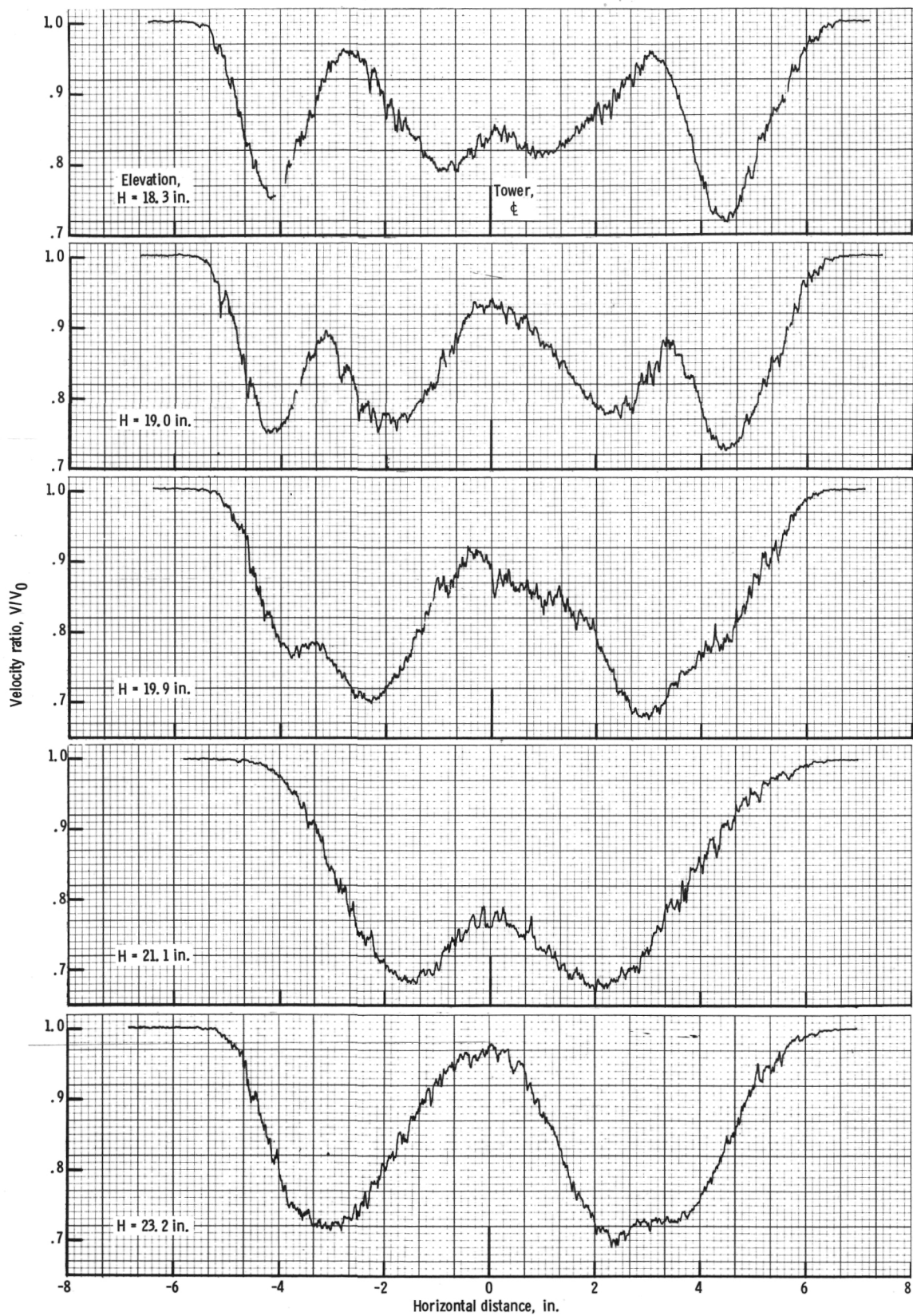
(a) Concluded.

Figure 18 - Continued.



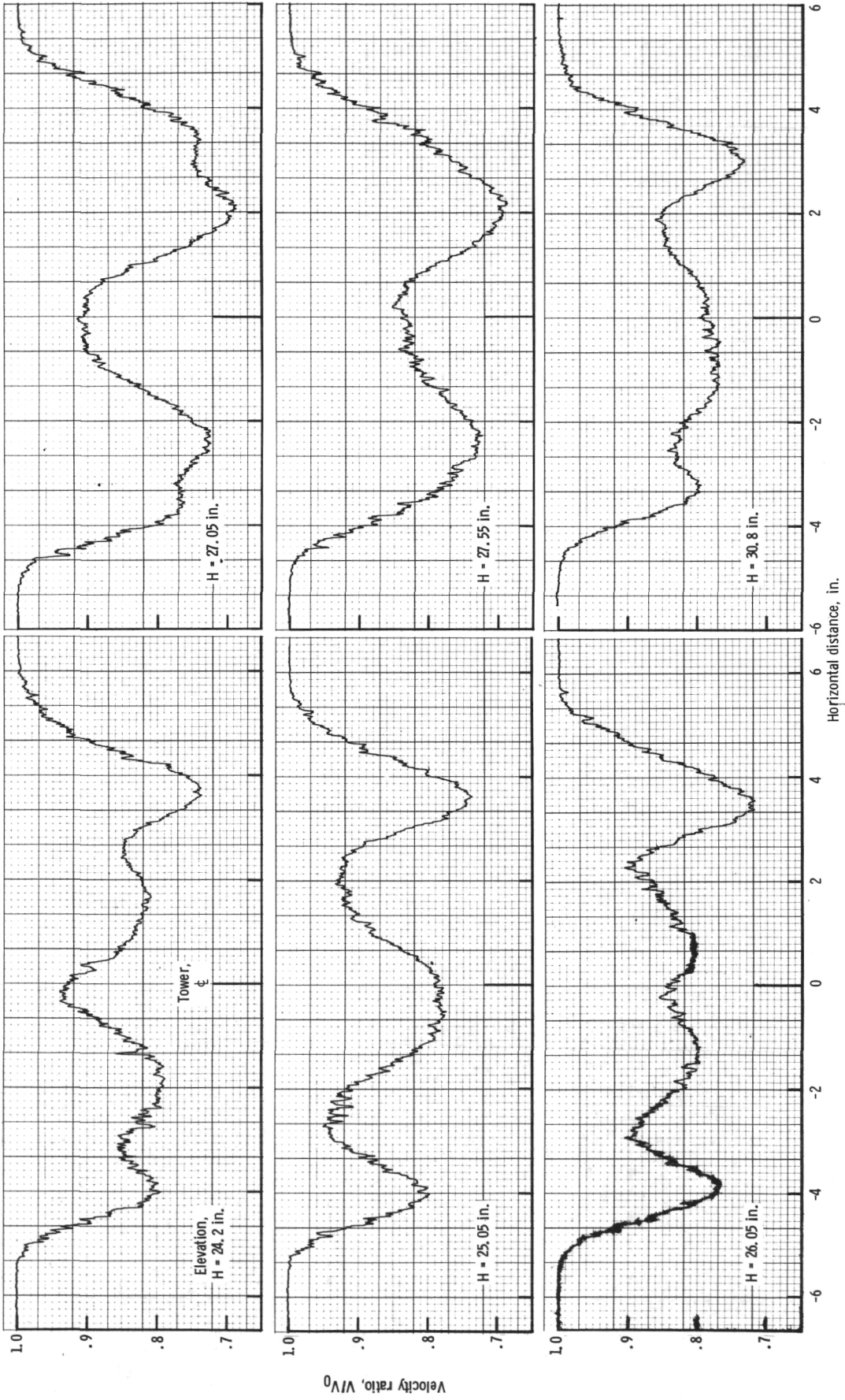
(b) Wind approach angle, $\theta = 5^\circ$.

Figure 18. - Continued.



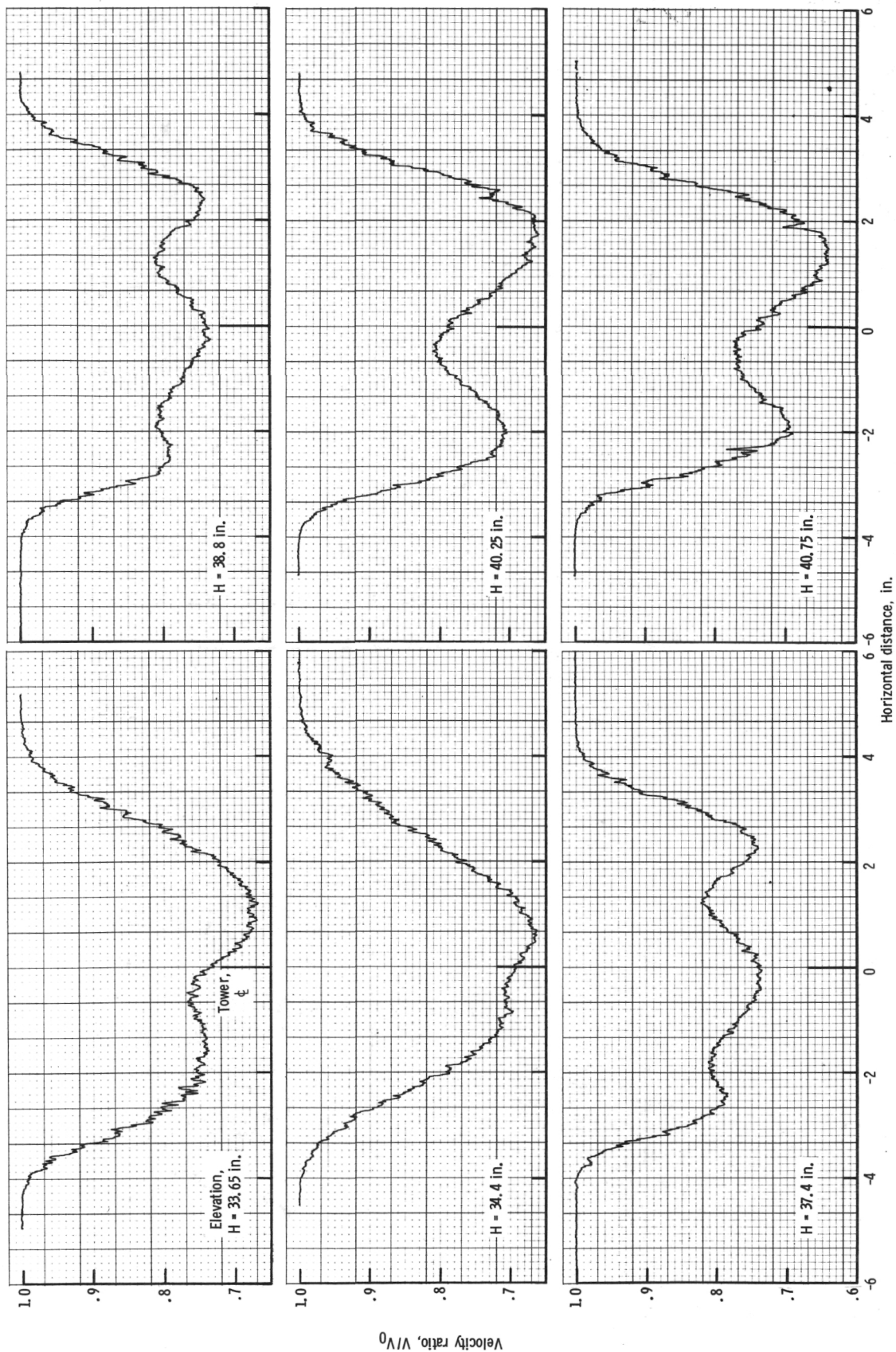
(b) Continued.

Figure 18. - Continued.



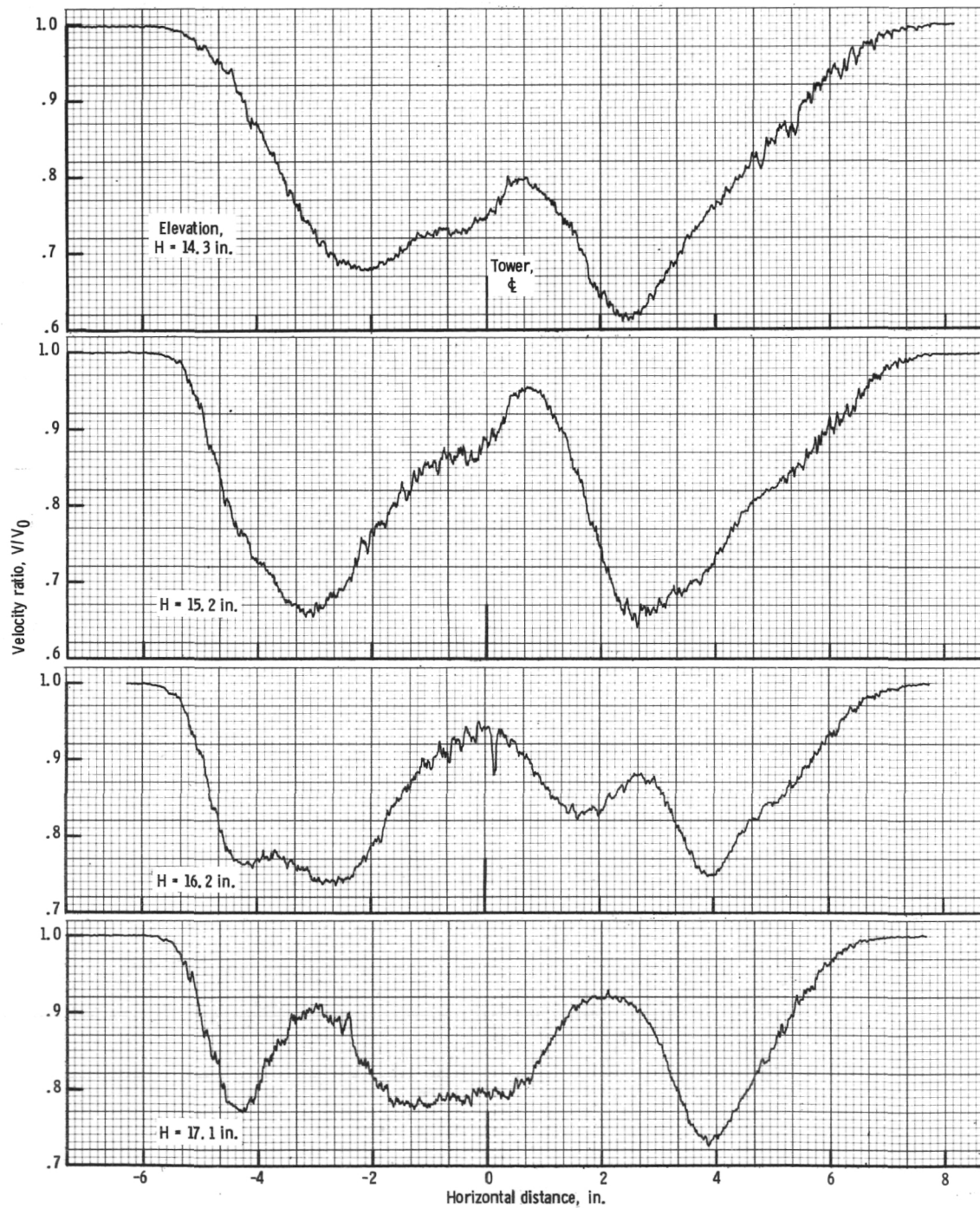
(b) Continued.

Figure 18. - Continued.



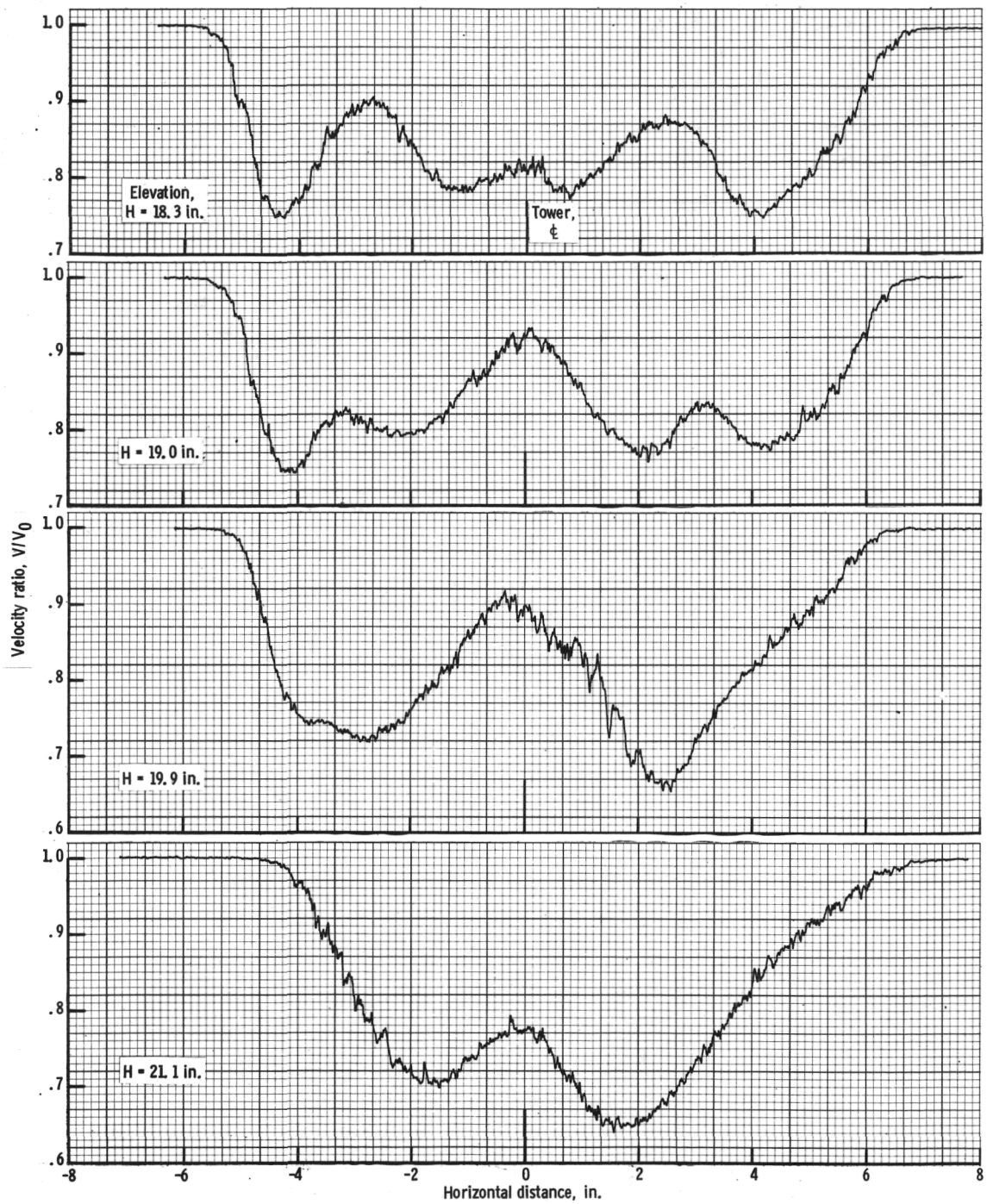
(b) Concluded.

Figure 18. - Continued.



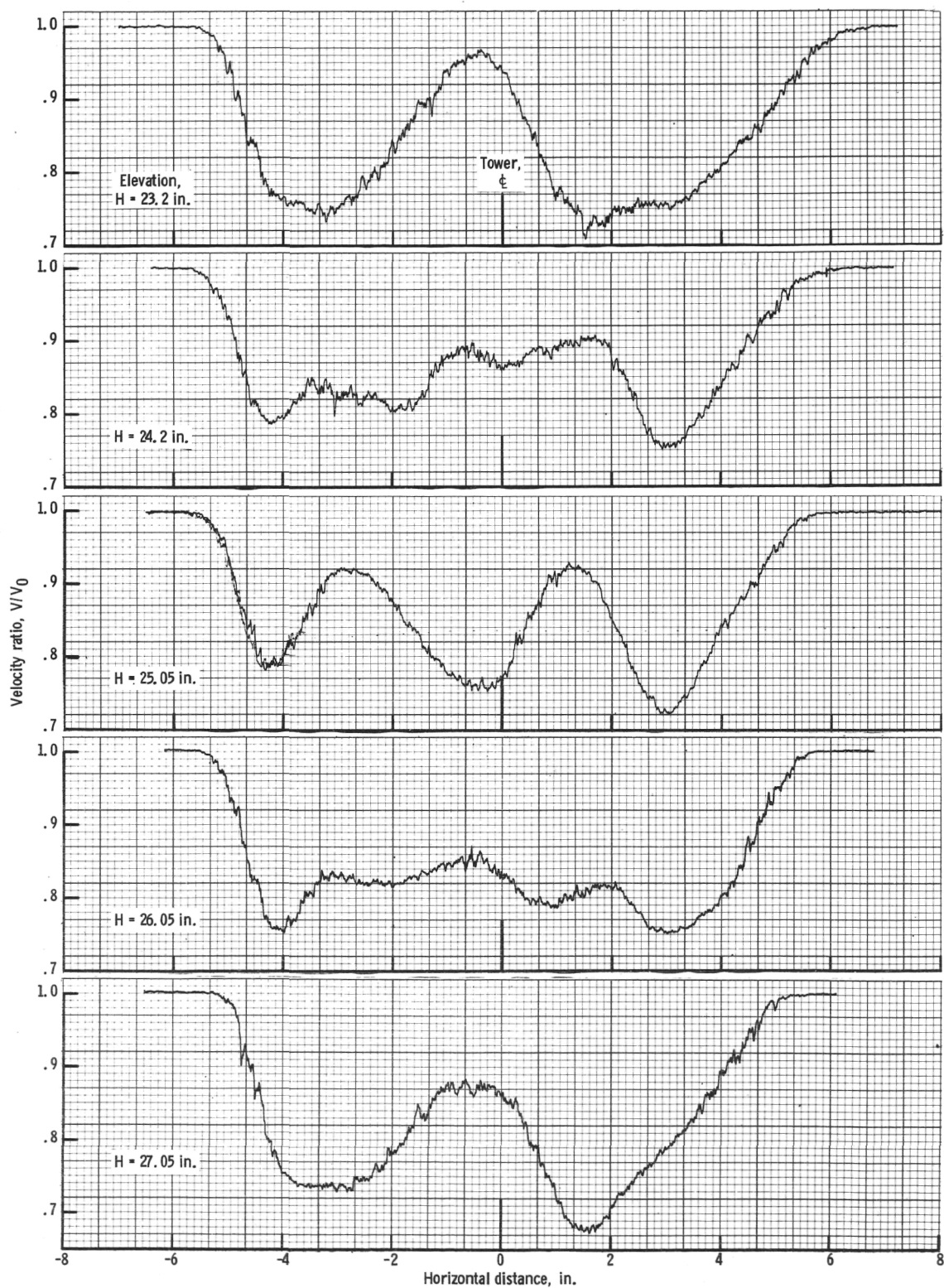
(c) Wind approach angle, $\theta = 10^\circ$.

Figure 18. - Continued.



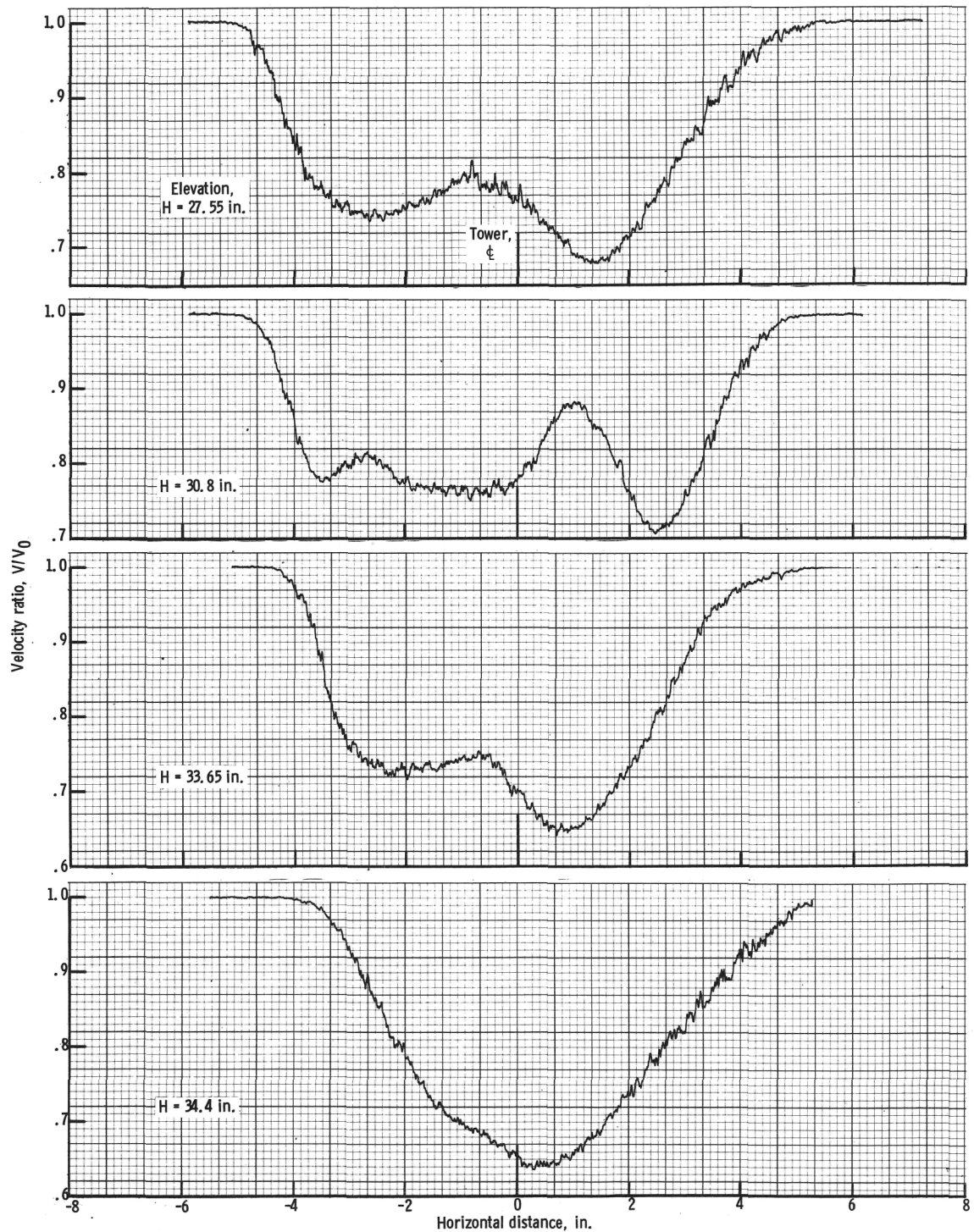
(c) Continued.

Figure 18. - Continued.



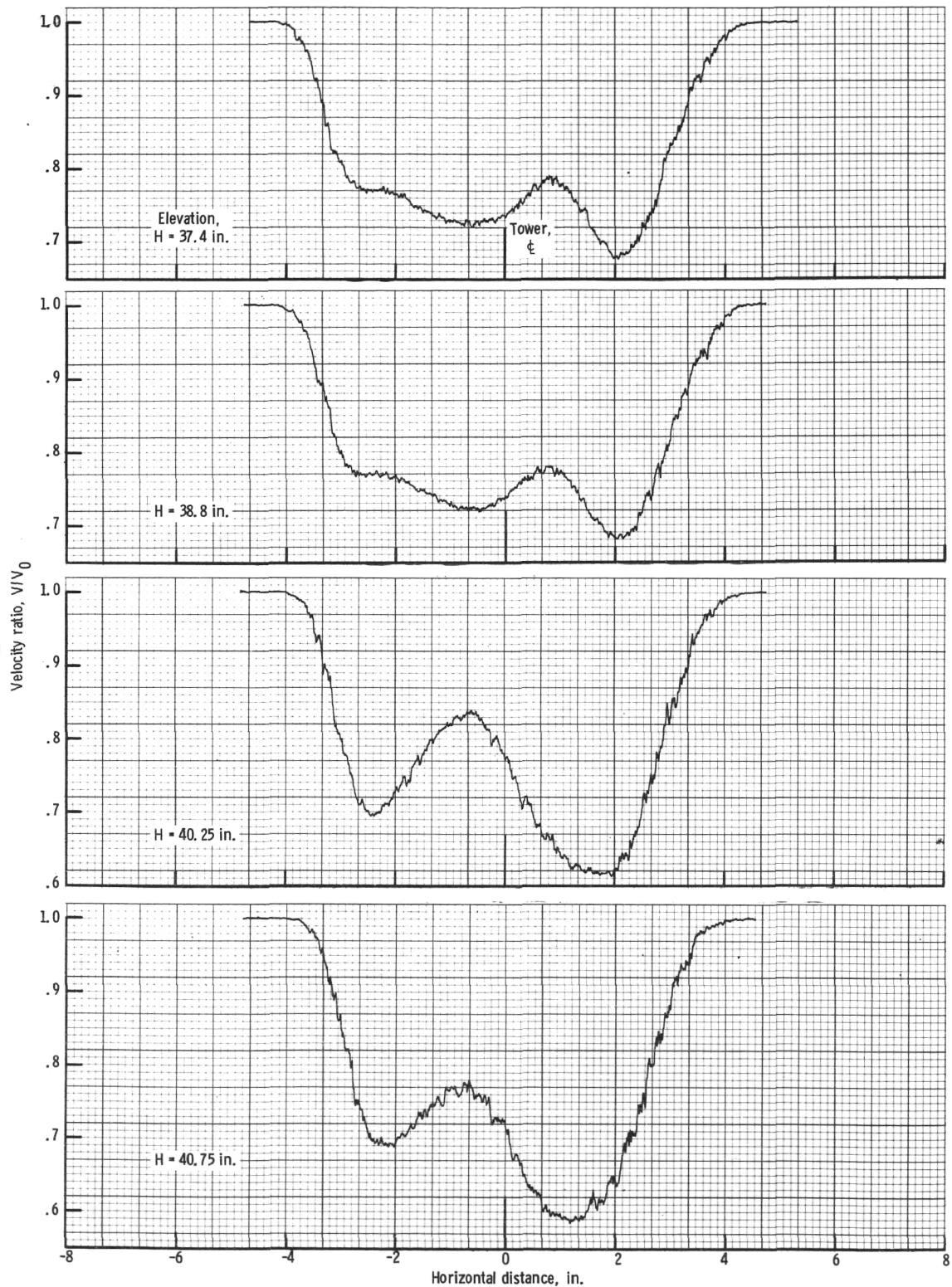
(c) Continued.

Figure 18. - Continued.



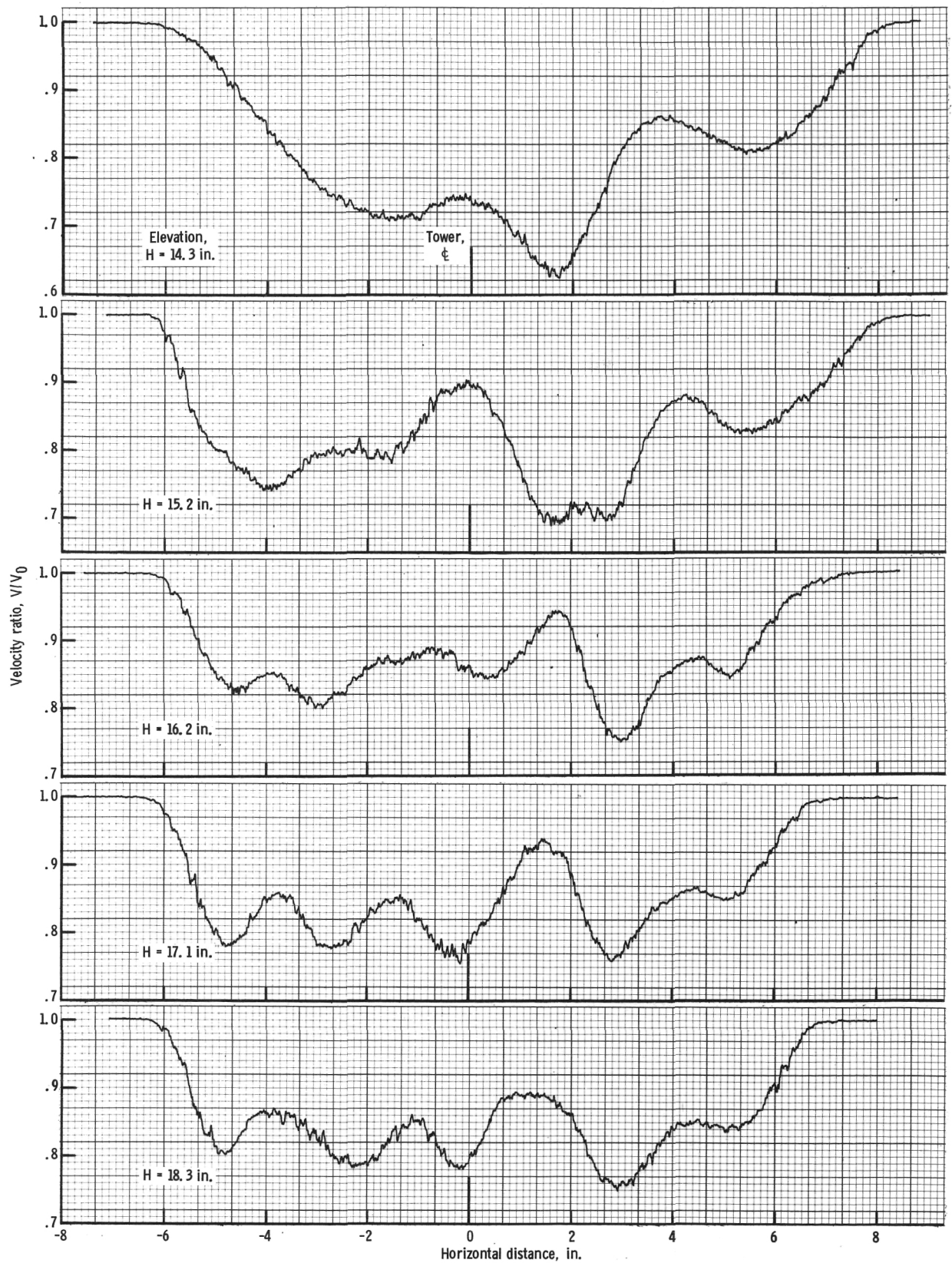
(c) Continued.

Figure 18. - Continued.



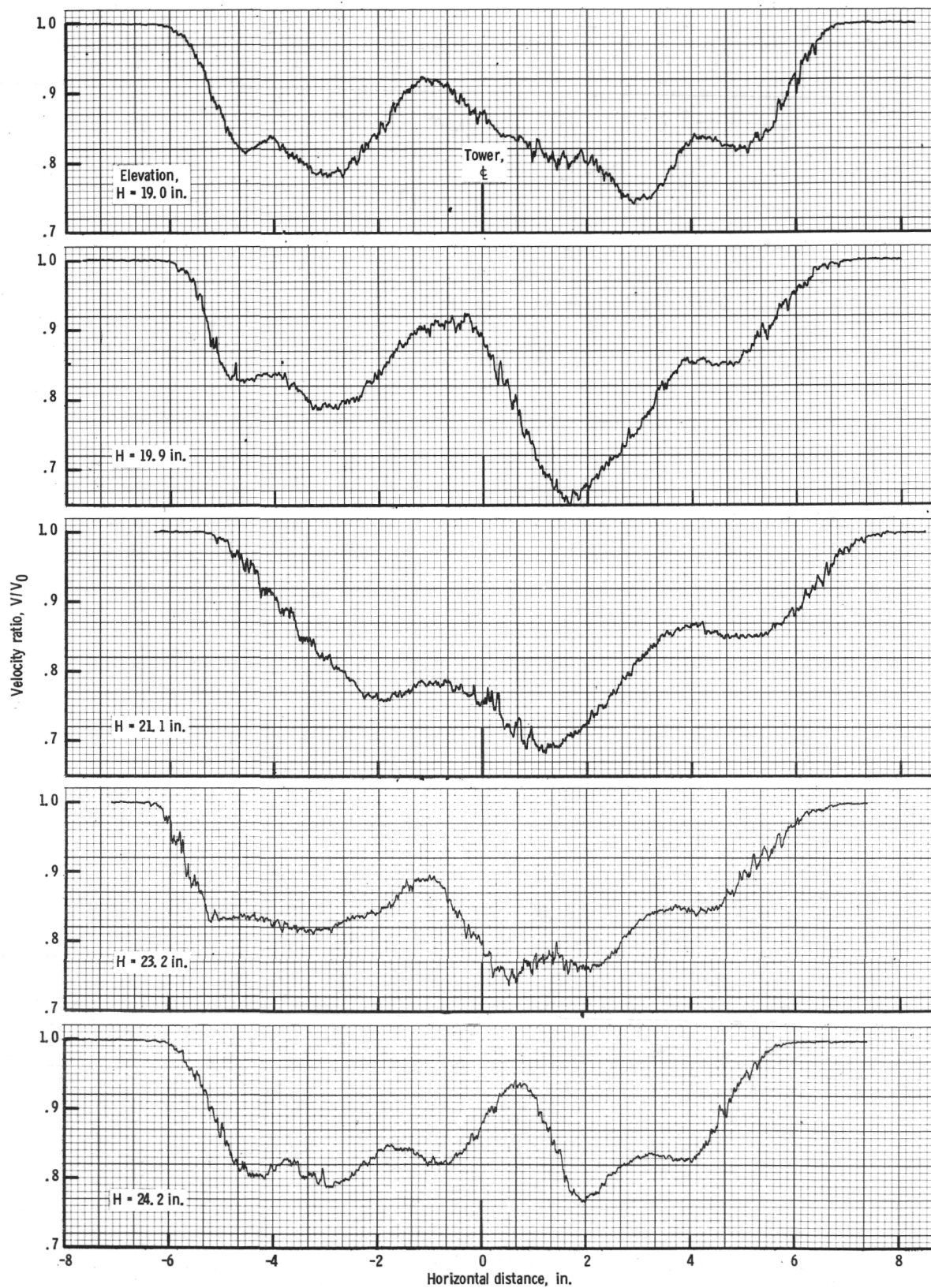
(c) Concluded.

Figure 18. - Continued.



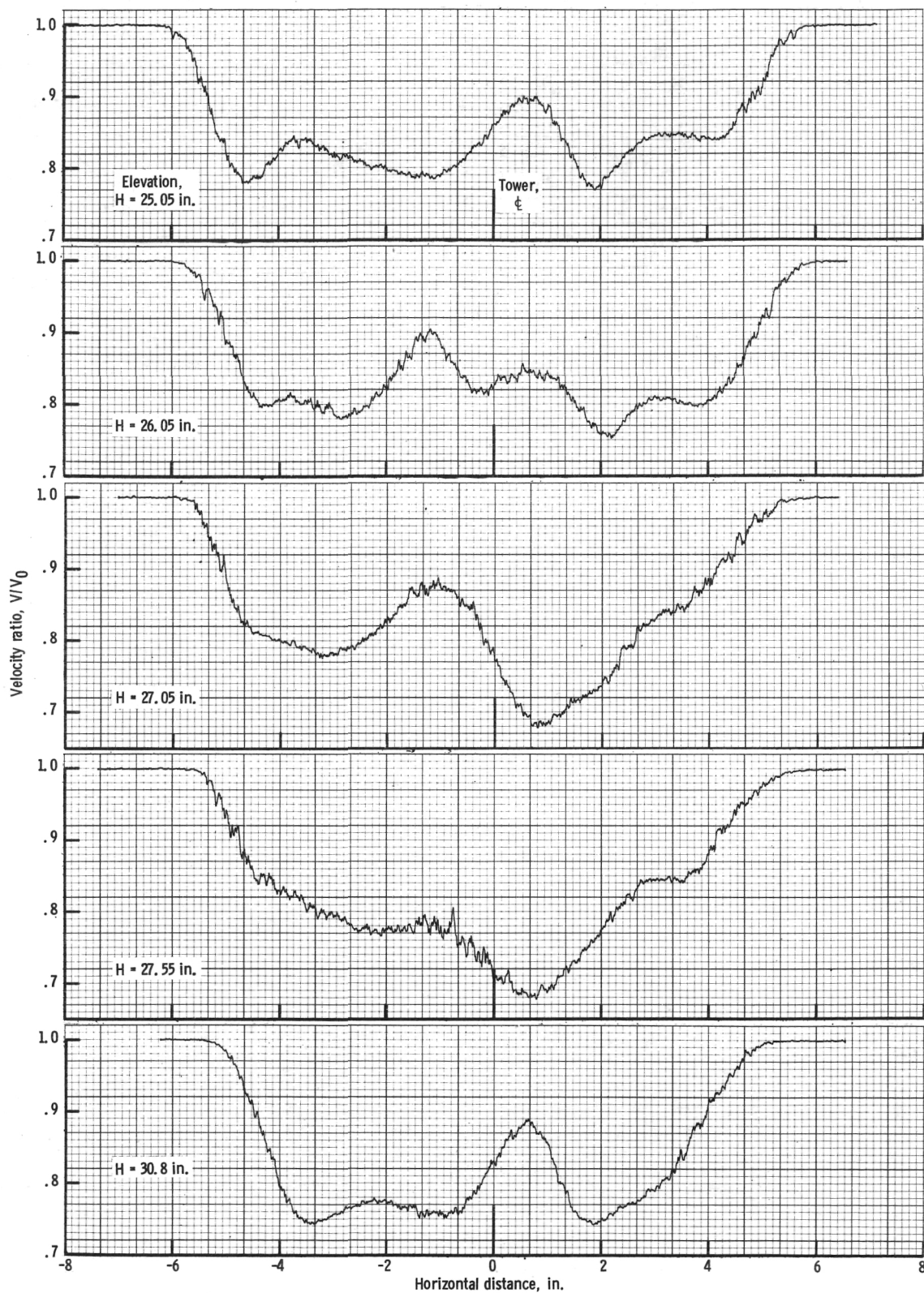
(d) Wind approach angle, $\theta = 20^\circ$.

Figure 18. - Continued.



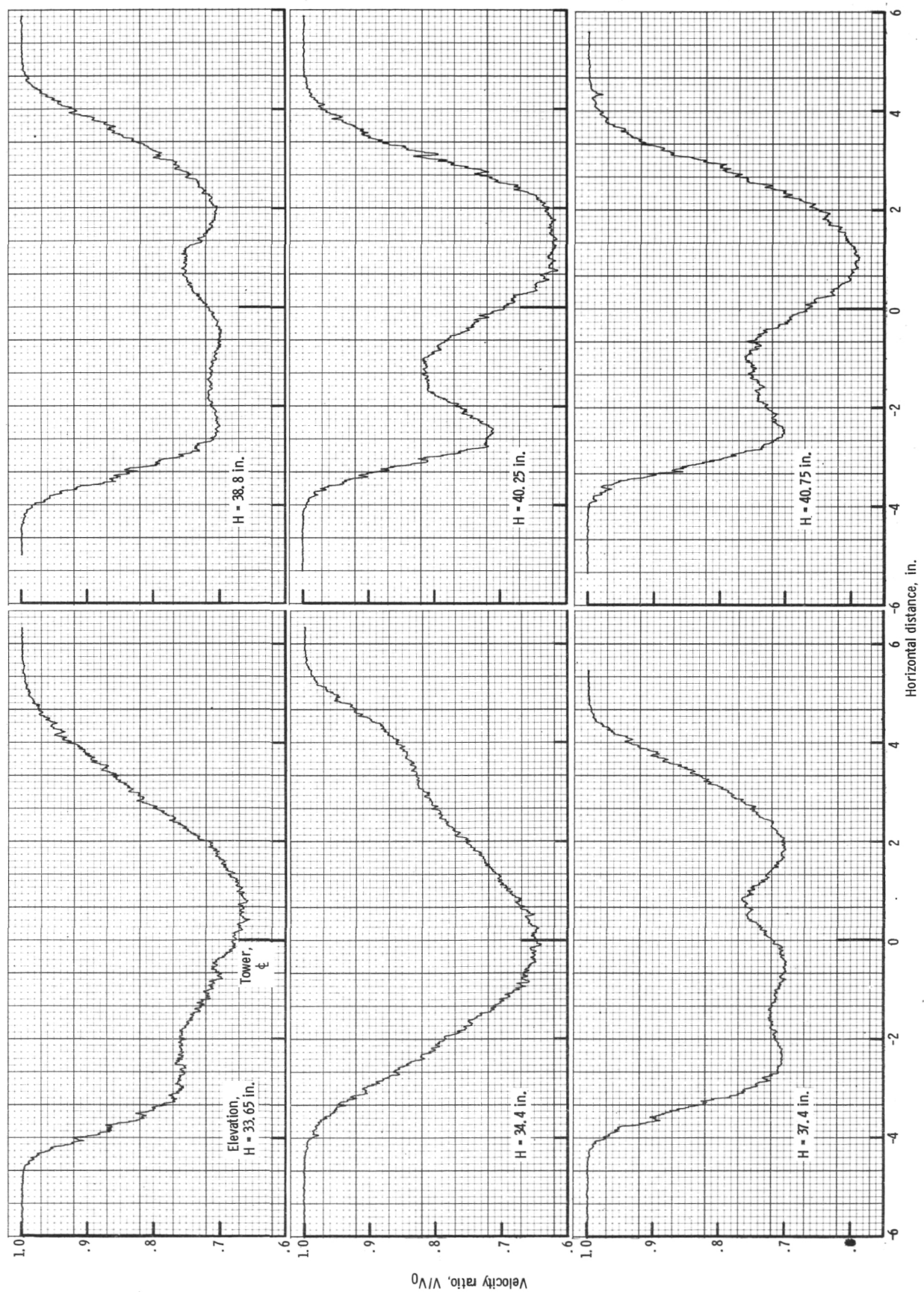
(d) Continued.

Figure 18. - Continued.



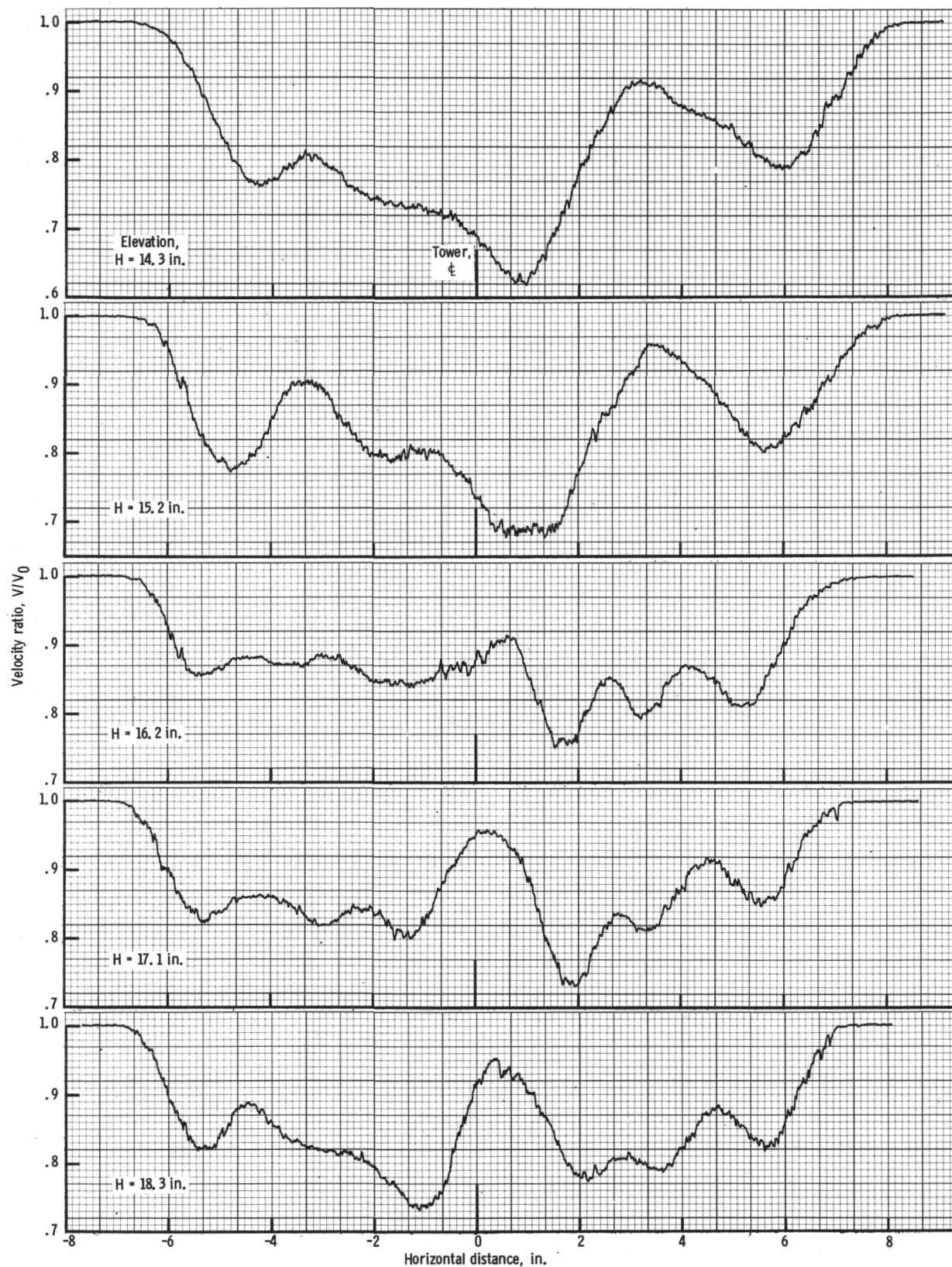
(d) Continued.

Figure 18. - Continued.



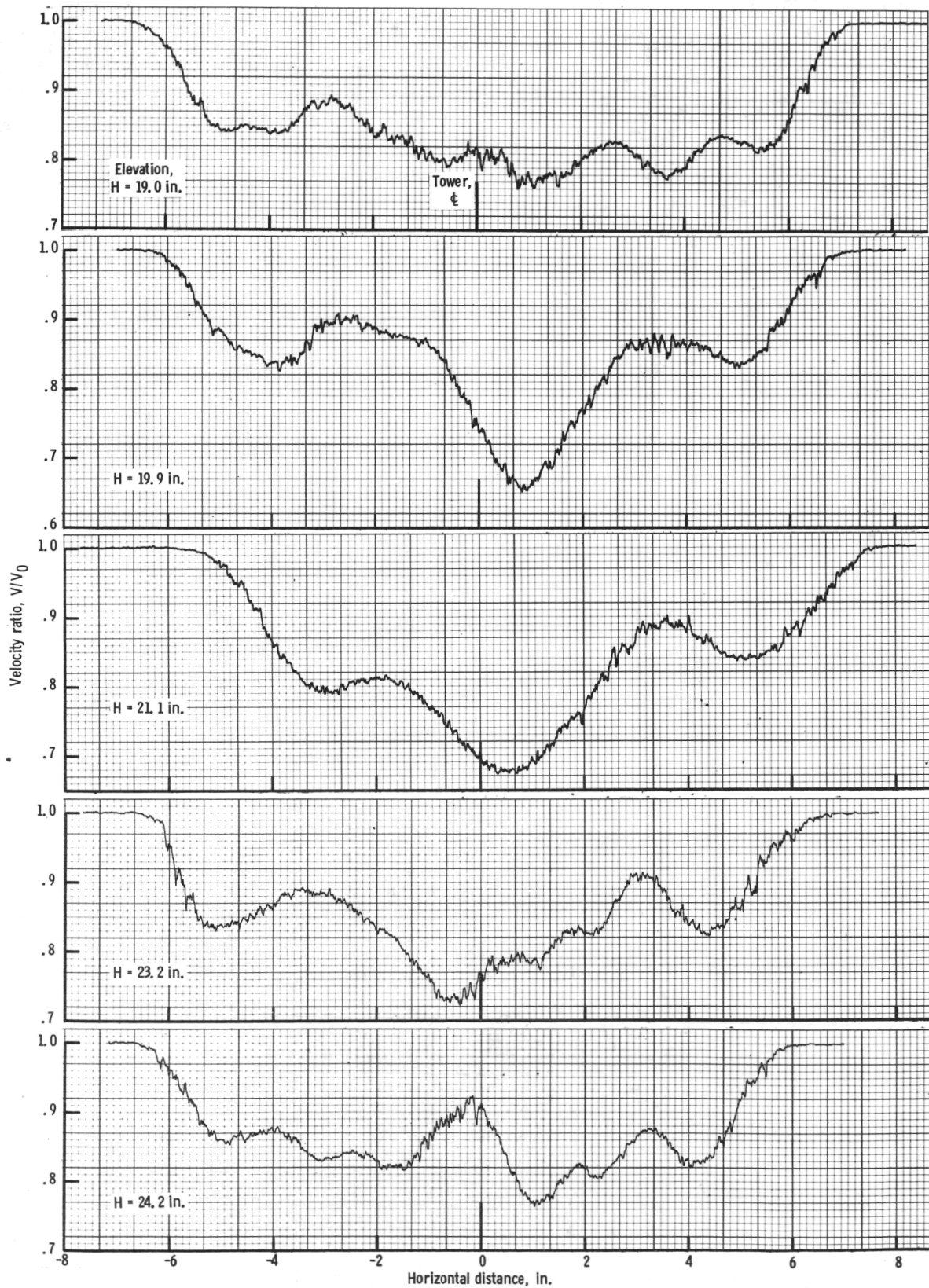
(d) Concluded.

Figure 18. - Continued.



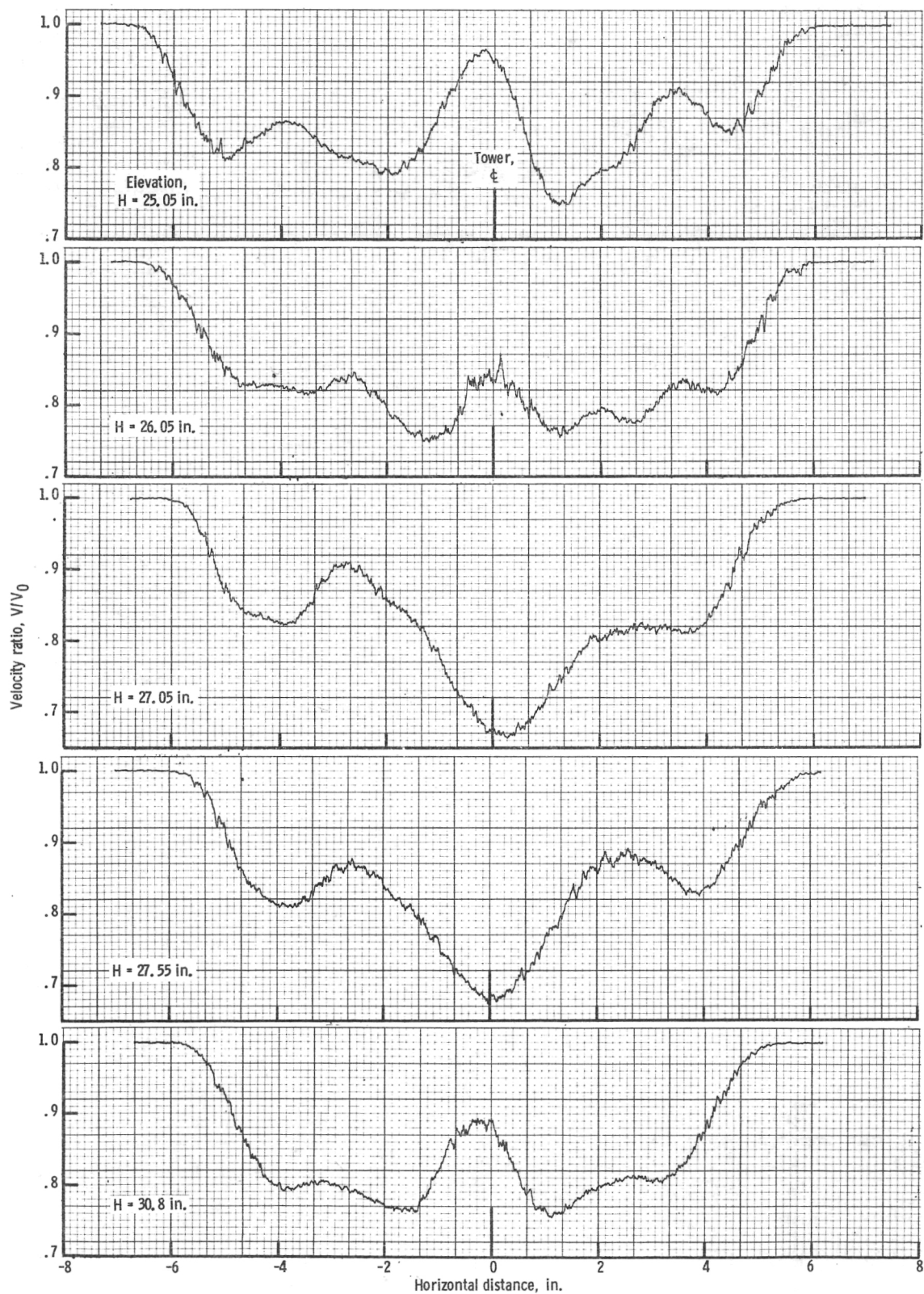
(e) Wind approach angle, $\theta = 30^\circ$.

Figure 18. - Continued.



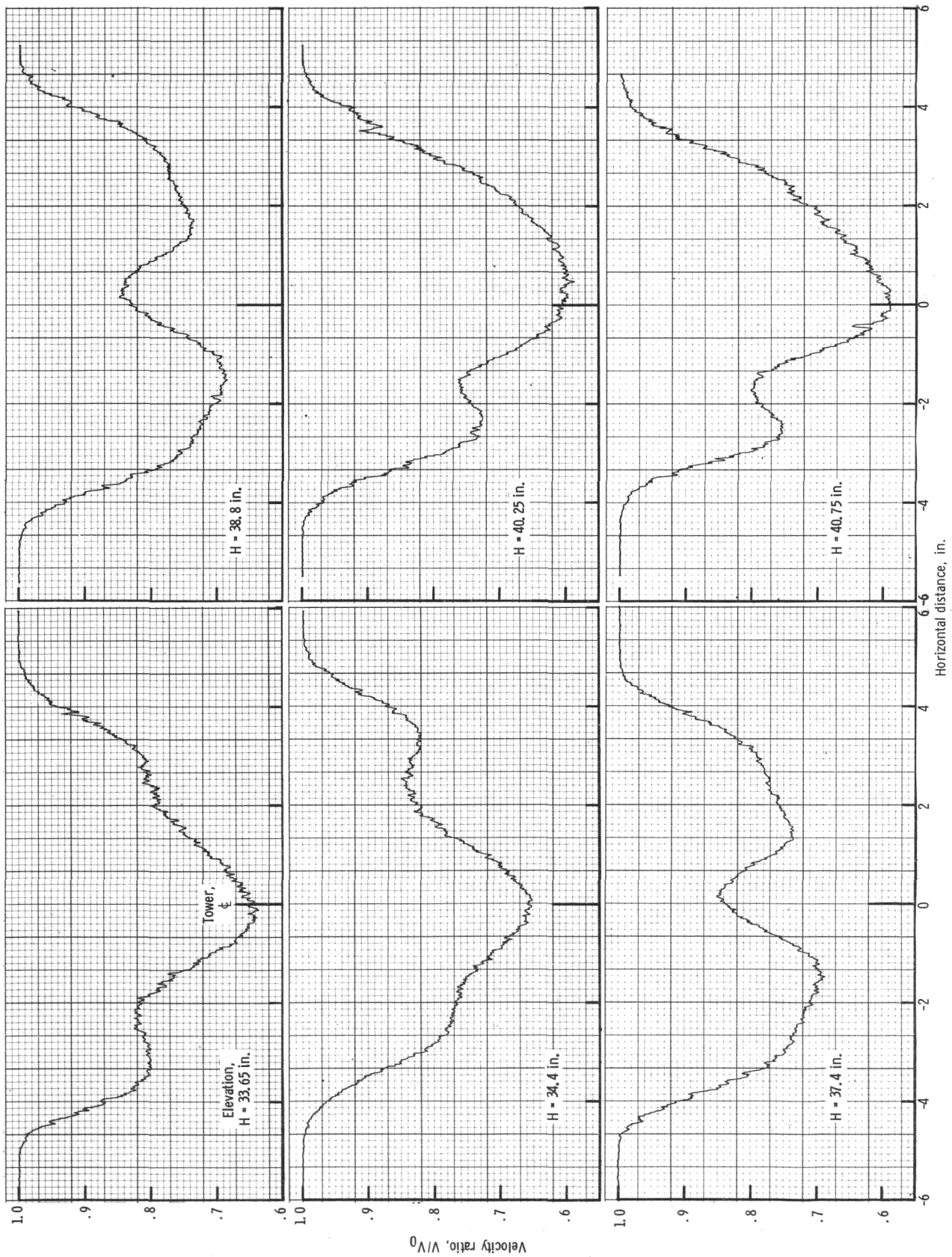
(e) Continued.

Figure 18. - Continued.



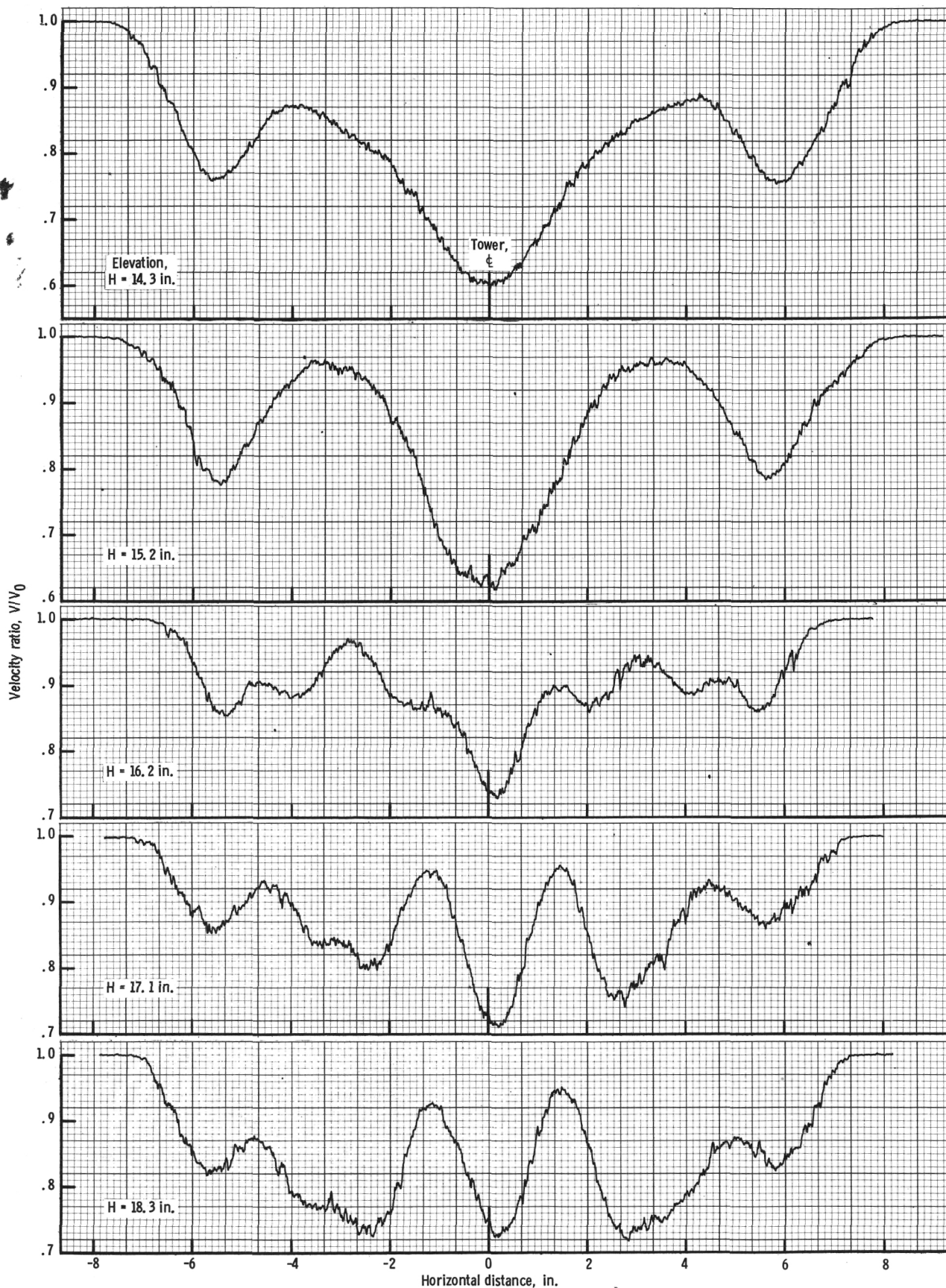
(e) Continued.

Figure 18. - Continued.



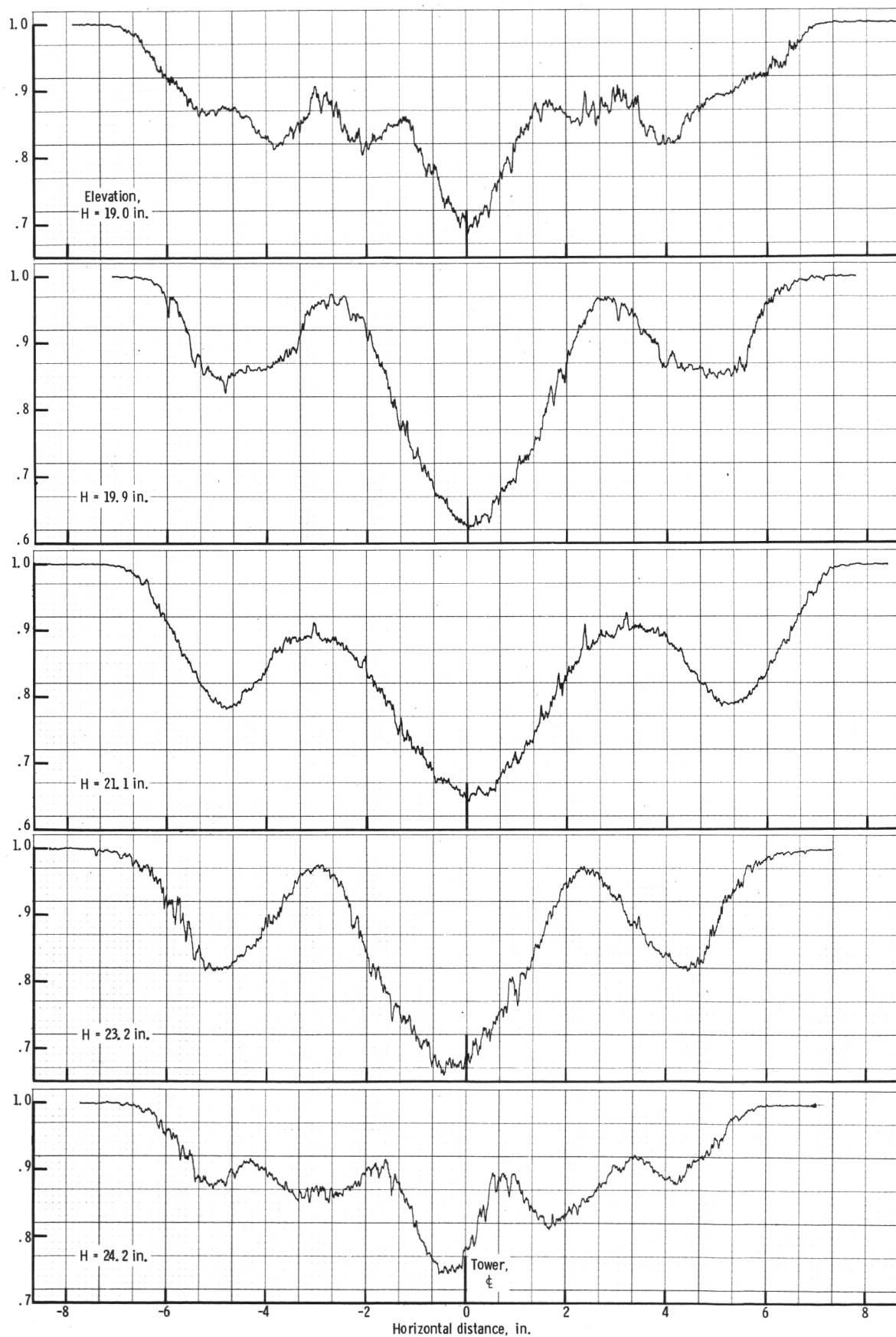
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Figure 18. - Continued.



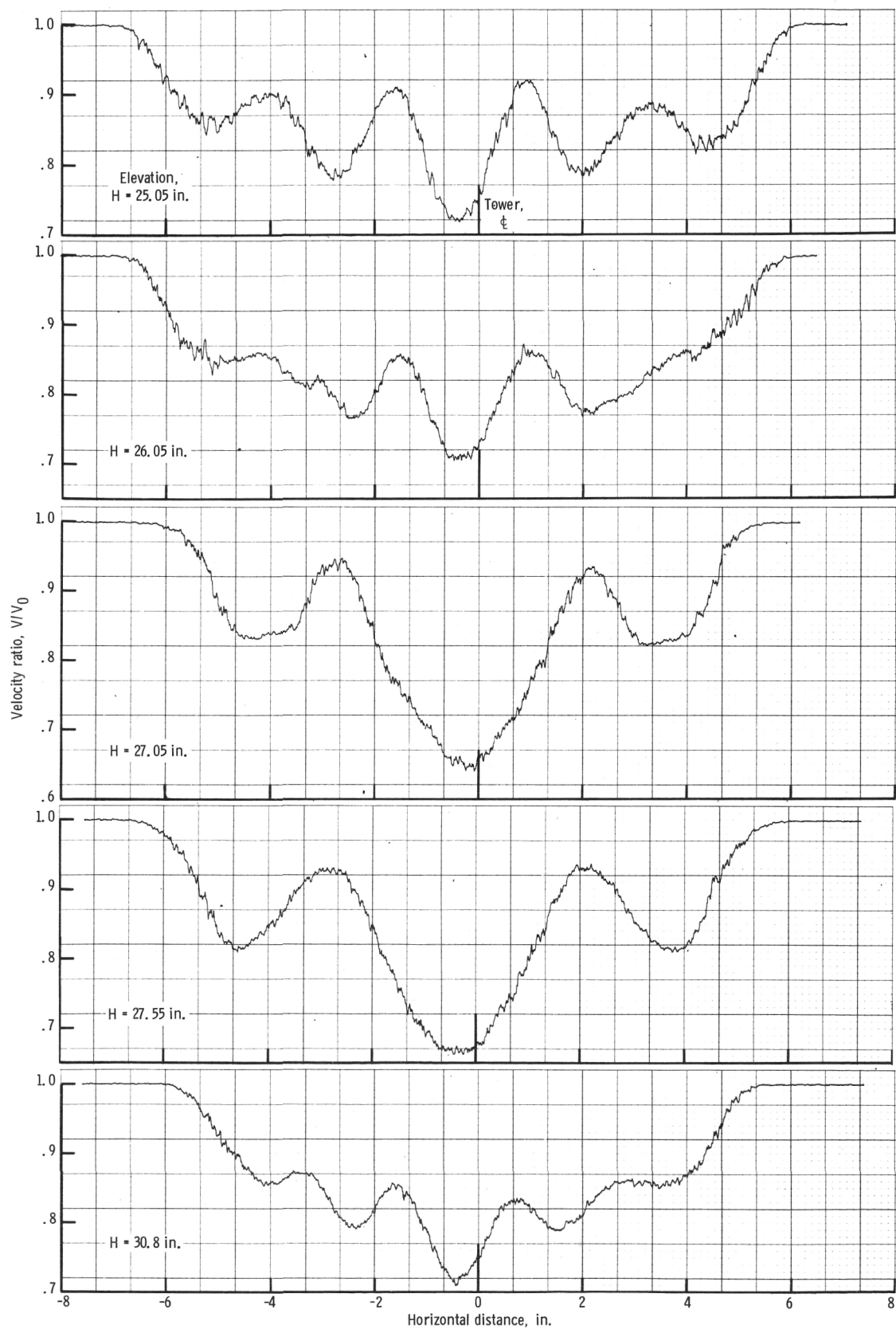
(f) Wind approach angle, $\theta = 45^\circ$.

Figure 48. - Continued.



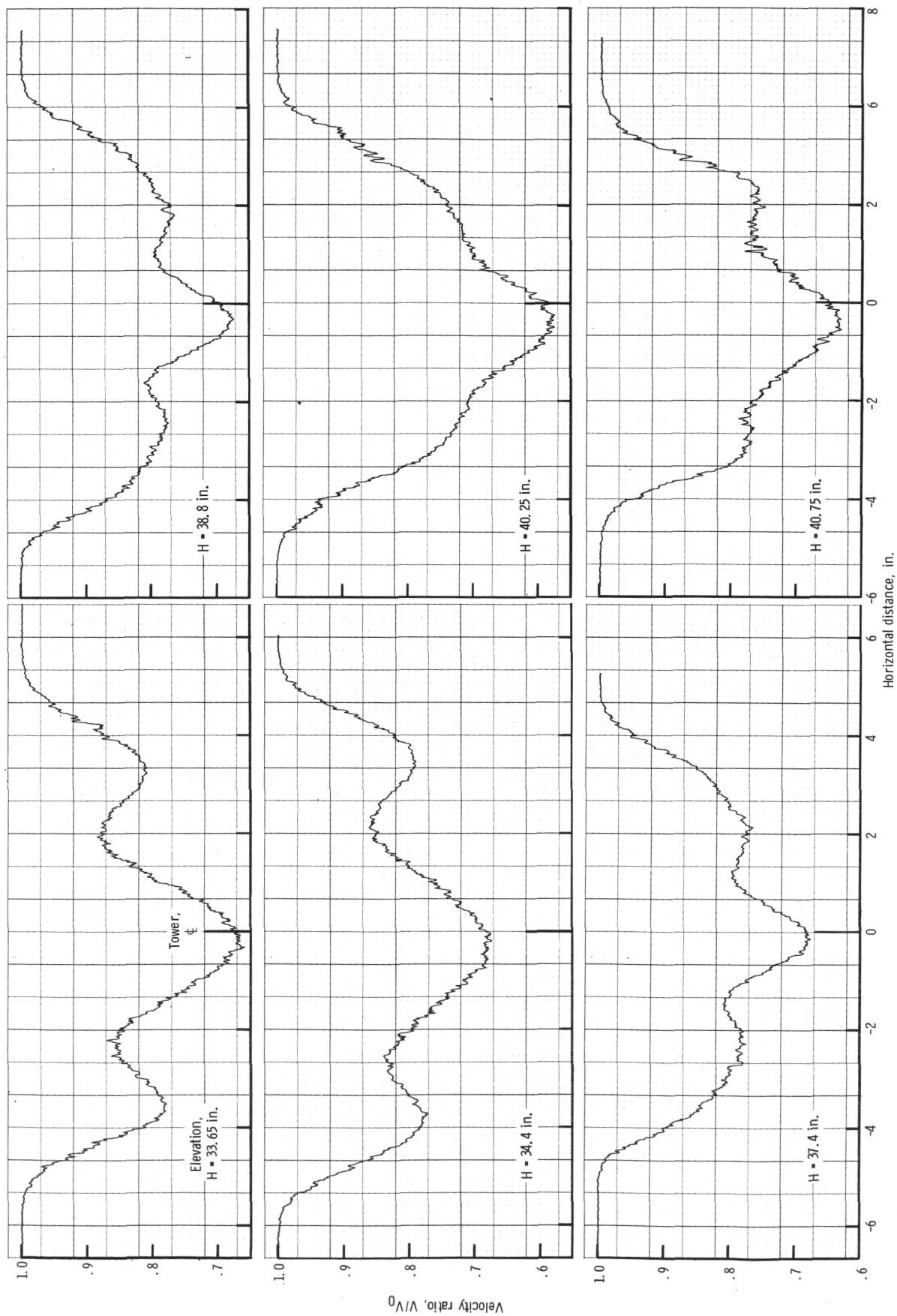
(f) Continued.

Figure 18. - Continued.



(f) Continued.

Figure 18. - Continued.



(f) Concluded.

Figure 18. - Concluded.

1. Report No. NASA TM-78853		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle WAKE CHARACTERISTICS OF A TOWER FOR THE DOE-NASA MOD-1 WIND TURBINE				5. Report Date April 1978	
				6. Performing Organization Code	
7. Author(s) Joseph M. Savino, Lee H. Wagner, and Mary Nash				8. Performing Organization Report No. E-9575	
				10. Work Unit No.	
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135				11. Contract or Grant No.	
				13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address Department of Energy Division of Solar Energy Washington, D. C. 20545				14. Sponsoring Agency Code Report No. DOE/NASA/1028-78/17	
15. Supplementary Notes Prepared under Interagency Agreement E(49-26)-1028. This report was prepared with the assistance of Seymour Lieblein of Technical Report Services, Rocky River, Ohio 44116.					
16. Abstract A 1/40th-scale model of a tower concept designed for the DOE-NASA MOD-1 wind power turbine was tested in a low-speed wind tunnel. Wake wind speed profiles were measured, and from these were determined local values of wake minimum velocity ratio, average velocity ratio, and width over a range of tower elevations and wind approach angles. Comparison with results from two other all-tubular models (MOD-0 and eight-leg designs) tested earlier in the same tunnel indicated that wake width and flow blockage at the rotor plane of rotation were slightly larger for the MOD-1 tower than for the other two models. The differences in wake characteristics were attributed to differences in tower geometry and member dimensions.					
17. Key Words (Suggested by Author(s)) Wind turbine Support tower Wake characteristics			18. Distribution Statement Unclassified - unlimited STAR Category 44 DOE Category UC-60		
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages	
				22. Price*	

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